Heat Roadmap Finland

Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps

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Nomenclature

Scenarios

BL 2015	Baseline Scenario for 2015
BL 2050	Baseline Scenario for 2050
CD 2050	Conventionally Decarbonised Scenario
HRE 2050	Heat Roadmap Europe Scenario for 2050

Country Codes

EU	European Union
HRE4 Countries	The 14 largest EU member states in terms of heat demand, totalling 90% of the EU heat demand.
FI	Finland

Abbreviations

CCS	Carbon Capture Storage
CHP	Combined heat and power
CO_2	Carbon dioxide
COP	Coefficient of performance
DH	District heating
HP	Heat pump
HRE	Heat Roadmap Europe project series starting in 2012
HRE4	Heat Roadmap Europe 4 (H2020-EE-2015-3-MarketUptake)
MS	Member States (of the European Union)
PES	Primary energy supply: all energy that is used, before conversion, as input to supply the energy system
PV	Photovoltaic
RES	Renewable energy sources

Introduction

The aim of Heat Roadmap Europe 4 (HRE4) is to create the scientific evidence required to support the decarbonisation of the heating and cooling sector in Europe and to redesign this sector by combining the knowledge of local heating markets, potential savings and energy system analysis. In particular, HRE4 aims to develop low-carbon heating and cooling strategies, called Heat Roadmaps, for 14 European Union member states (including Finland) and allow for a better understanding and more accurate quantification of the European heating and cooling sector. The project covers countries equivalent to 90% of the European heat demands.

Key to the project is the combination of mapping and energy system modelling, in order to be able to understand not just the system effects of energy efficiency but also the spatial dimension. Therefore, the approach in HRE4 brings together energy system analysis with spatial planning tools and provides an in-depth understanding of thermal demands in built environment and industry, including both heating and cooling.

HRE4 involves the most detailed spatial mapping of heat demands and renewable heat resources up to date; includes the potential for reducing heat demands through cost-efficient energy efficiency measures in both the heating and the cooling sector; integrates industrial sectors to quantify heat demands; and models both long term projections and hour-by-hour energy systems.

In addition to this report, which described the specific findings and Heat Roadmap for Finland, a variety of tools, methodologies and datasets have been developed in the context of the HRE4 project which are available at www.heatroadmap.eu and can provide further detail and background:

- A final report presenting the heating and cooling scenarios in HRE4, and 14 country reports.
- An updated version of the Pan-European Thermal Atlas, including Finland.
- An interactive dataset on the profiles for heating and cooling demands in Europe, breaking down the heating and cooling sector by demand type, sector, industry, and temperature, including for Finland.
- 56 freely available energy system simulation models (including 4 for Finland), and an interactive dataset showing some of the key results.
- Deliverables on the methodologies, data, and capacity-building activities related to the HRE4 project.

The main aim of the Heat Roadmap scenarios is to demonstrate and understand how to cost-effectively use energy efficiency, be decarbonised, and design a pathway for decarbonised heating and cooling that fits within a broader decarbonised energy system. This means that the heating and cooling system is decarbonised in a way that enables the electricity sector to further decarbonise (for example by providing further flexibility for the effective integration of variable renewable sources), and that does not stand in the way of further decarbonisation of the transport and industry sectors by using unnecessary amounts of bioenergy.

The scenarios all cover the heating, cooling, industry, electricity and transport sector, but in the analysis focus primarily on what can be achieved in the heating, cooling, industry, and power sector. The scenarios are compared and assessed along several parameters, rather than being cost-optimised within various (qualitatively considered) constraints. These parameters in Heat Roadmap Finland are the following:

- **Decarbonisation**: CO_2 emissions that result from the energy system, indicating a level of decarbonisation. Collectively for the HRE14, which represent 90% of the heat demand, this means contributing to the long-term goal of the EU towards 95% reduction in CO_2 emissions compared to 1990 levels in order to be in line with the Paris Agreement from 2015 and a nearly zero carbon energy system.
- **Efficiency:** Primary energy is used as an indicator of the efficiency of the system, to understand how much energy is needed overall to fulfil the demands and comforts of the energy system. This differs from approaches which use final or delivered energy, which only considered how much energy is needed within the building or process itself. By considering primary energy, a more holistic and comprehensive view is taken on how to decarbonise the energy system as a whole.
- **Economy:** Socio-economic annualised costs are used to indicate the affordability and competitiveness of the various systems, from the perspective of society at large. In this way, the full cost of building, maintaining, and running energy technologies and infrastructures with different lifetimes is considered. However, the use of socio-economic costs means that market interventions may be necessary to ensure that market prices reflect the real cost (for example in the case of carbon emissions), and to ensure that the market reallocates the costs and benefits that arise from a new system design in a fair way.
- **Environment:** Attention is given to limit bioenergy and biomass consumption, to indicate the reliance on (scarce) resources that may not fit stronger sustainability principles. This is especially the case for bioenergy which is grown in areas that may displace food production or lead to land-use changes, and imported bioenergy.

The energy system scenarios analysed and presented in this report are:

- The Baseline 2015 scenario (BL 2015), which is a representation of the current energy system,
- The Conventionally Decarbonised 2050 scenario (CD 2050), which represents the development of the energy system under a framework that encourages renewables, but does not radically change the heating and cooling sector,

- The Heat Roadmap Finland 2050 scenario (HRE 2050), which represents a redesigned heating and cooling system, considering different types of energy efficiency and better integration with the other energy sectors.

For more details about these scenarios, see main report of Deliverable 6.4 [1].

About Heat Roadmap Europe

Heat Roadmap Europe 4 follows as instalment a series of previous studies that have been carried out since 2012 [2–4], which have resulted in a total of 18 different reports, primarily relating to the long-term changes that are necessary to implement in order to decarbonise the heating and cooling sector in Europe. The acronyms 'HRE' and 'HRE4' are used for brevity and consistency, where '4' distinguishes the new data and methodological improvements produced during this current study, as HRE4 builds on the foundation set by the three previous studies and expands its research scope in terms of both energy sectors and geography.

HRE4 project with a consortium of 24 partners has received funding from the European Union's Horizon 2020 research and innovation programme since 2016 until 2019. It addresses the topic EE-14-2015 "Removing market barriers to the uptake of efficient heating and cooling solutions" of the Energy-efficiency call, by quantifying the effects of increased energy efficiency on both demand and supply side, in terms of energy consumption, environmental impacts and costs.

In order to fulfil Coordination and Support Action Grant objectives and requirements, HRE4 has been executing a strategy of dissemination measures in order to communicate the research findings to the relevant stakeholders, who by position and profession can use the scientific evidence for facilitating the market uptake of efficient and sustainable developments in heating and cooling sectors. Thus, on the one hand HRE is advancing on scientific research which:

- Involves the most detailed spatial mapping of heat demands and renewable heat resources up to date;
- Includes the potential for reducing heat demands through cost-efficient energy efficiency measures in both the heating and the cooling sector;
- Integrates industrial sectors to quantify heat demands;
- Models both long term projections and hour-by-hour energy systems.

On the other hand, it is heavily occupied with measures for coordination and support as:

- Developing user manuals of the research findings and tools, as a way to standardise new knowledge and render it intelligible to non-scientific officials;
- Hosting workshops, strategic panel discussions where policy-makers are invited;
- Participating in events, as conferences, for promotion of project tools and findings;
- Active presence on social media, where the results are communicated to broader audiences;
- Awareness-raising activities in the digital media, such as informative videos and instructional webinars.

Summary of results in Heat Roadmap Finland

The scenario and results for Heat Roadmap Finland represent a technically feasible, economically viable alternative which could contribute to the deep decarbonisation of the Finnish energy system. It considers only proven technologies to achieve reductions in heating and cooling demand, more efficient supply systems, and to integrate a higher level of renewables, and does not rely on unsustainable amounts of bioenergy.

The approach is based on combining energy efficiency on the demand and the supply side of the heating and cooling sector and deeper integration, as a way to achieve deep decarbonisation of the sector. Both savings on the heating and cooling demand side are considered in the form of high standards for the energy performance of buildings and renovation rates, and the efficient supply of heating and cooling through heat pumps, efficient chillers, and district heating and cooling. Iterative simulations are done to determine the optimal levels of different types of the main energy efficiency and decarbonisation measures. This redesign of the heating and cooling sector is then integrated with the wider energy system; in particular, the industry and electricity sectors.

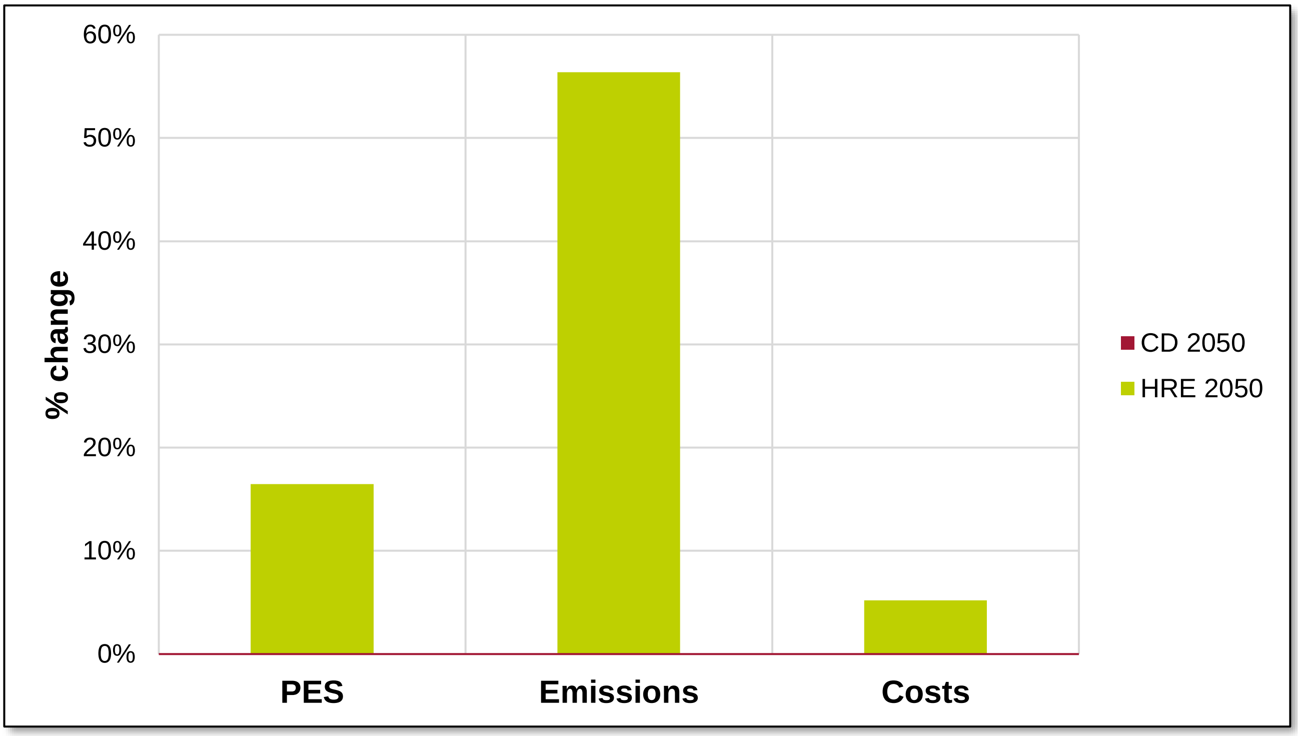


Figure 1. Percentage improvement in efficiency, energy and industry related emissions and system costs of Heat Roadmap Finland (HRE 2050) compared to the conventionally decarbonized scenario (CD 2050).

Based on these measures proposed in Heat Roadmap Finland, it is possible to decarbonise the energy system and reduce the energy demand, carbon emissions, and costs of the Finnish energy system compared to a conventionally decarbonised 2050 scenario (see Figure 1). Heat Roadmap Finland allows for:

- **Deep decarbonisation** of the energy system, achieving a 103% reduction of carbon emissions compared to 1990 levels through higher levels of energy efficiency and a redesign of the heating and cooling sector as well as accounting for carbon sinks in non-energy. Compared to conventional decarbonisation, the energy and industry related emissions decrease by 56%.
- **Higher levels of efficiency**, with a 16% advantage over a conventionally decarbonised energy system. This is due to end-user energy savings, the recovery of different types of heat and cold in thermal networks, and a better integration between the heating, cooling and electricity sectors.
- **Lower energy system costs**, mostly due to hugely reduced fuel costs. While certain areas will require higher levels of investment (notably investments for heat savings measures, building level heat pumps, and district energy systems), Heat Roadmap Finland saves over €1,5 billion annually.

The scenarios in Heat Roadmap Finland have been developed using the data, methodologies, knowledge and approaches developed throughout the HRE4 project. This includes a detailed spatial analysis in order to be able to understand the local nature of heating and cooling, and in order to more accurately appreciate infrastructure costs. This is especially important when considering district energy, since the cost of infrastructure is proportionally higher than the cost of supplying the energy.

In addition, an in depth understanding of the thermal sector and thermal demands is required, since they are often overlooked in standardised statistics. This is both the case for heating, where knowledge on the building stock is typically poor and district heating difficult to represent, and cooling, which is typically hidden within the electricity sector. This forms the base of any strategic heating and cooling development and underlies an understanding of what kinds of energy savings are possible.

These are combined in the development of the energy system scenario, since an energy system analysis approach is necessary in order to ensure that a decarbonised energy system does not exist in isolation. A coherent energy system design allows for the heating and cooling sector to be integrated into a wider decarbonised energy system and the synergies between the heating and cooling, industry, and electricity sector can be used. Together, this allows us to quantify the effect of energy efficiency within an integrated energy system.

Based on the data, knowledge, methodologies, and scenarios developed and made available by the HRE4 project, it is clear that the European Union should focus on implementing change and enabling markets for existing technologies and infrastructures in order to harvest the benefits of decarbonisation and improve the energy efficiency of the heating and cooling sector.

On the country level, action and implementation plans should include and develop adjustment efforts in order to consider approaches to 1) end-user savings, 2) thermal infrastructure expansion, 3) excess heat utilisation and heat production units, and 4) individual heat pumps outside urban areas. These are the main technologies that contribute to the efficiency, decarbonisation, and affordability of the heating and cooling sector.

End use savings are vital to efficiency, decarbonisation and affordability. This is particularly true for space heating in existing buildings, where higher renovation rates and depths are needed to reduce heat demands by 19%. The current level of ambition is high (set for a 15% demand increase by 2050), but the focus should be on country and/or regional level follow through on the effectiveness of policies and implementation strategies, in order to ensure that the EU and country level energy savings goals are met.

The **redesign of thermal grids** in the Finish energy system is crucial to enable better integration of renewable energy and excess heat sources in both urban and non-urban contexts. Finland currently has a large district heating share of 48% of the built environment (excluding DH for industry). However, from an economic perspective, Heat Roadmap Finland shows that it would be feasible to have district heating cover up to 52% of the built environment.

Excess heat recovery from industry and heat from power production is key to an efficient and resilient heating and cooling sector, and has the potential to support local industries, economies, and employment. This should cover at least 14% of the district heat production, and requires a concerted change in planning practices for local industries, waste incineration, future fuel production sites, and potentially also data centres, sewage treatment facilities and other types of non-conventional excess heat. Some excess heat requires heat pumps to supply the sufficient temperatures. This is included in the analyses. Taxation or technical barriers to use low-temperature waste heat from industry should be removed.

Future **production and storage units** for district heating must be more varied and versatile to integrate low-carbon sources and enable flexibility. Boilers should not produce more than 8% of the district heating demand so new planning approaches and policies should create level playing fields and encourage integration. The establishment of thermal storage should be integrated in the (re-)development of new thermal grids to increase the use of various renewables, different types of excess heat and the use of cogeneration and large scale heat pumps. Short-term storages are crucial to balance the electricity grid as well as to handle fluctuating local low value heat sources.

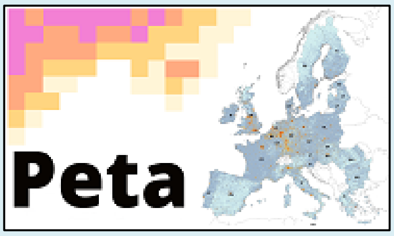
Individual heat pumps will be key to enabling efficiency and electrification in areas where district energy is not viable, and could provide roughly half of the heat for the built environment (excluding DH demand for industry). Since the investments required to unlock their potential is high and often borne by building owners, focus should be on policies and implementation strategies that encourage switching from individual (gas) boilers and inefficient electric heating to more efficient alternatives in non-urban areas. The small individual heat pumps can be combined with solar thermal and biomass boilers as a part of the supply. In this study all individual heating is supplied by heat pumps as a modelling method due to their distinct advantage of efficiency and integration with the electricity sector.

Detailed Description of Heat Roadmap Finland

Spatial Planning

An important aspect in heat planning is to realise the geographically explicit nature of heating. It is not possible to move large amounts of thermal energy over large distances without increasing transmission losses. The possible distances depend on the size of the application, and while large-scale district energy systems can have a reach of many kilometres, small systems in smaller towns need sources of thermal energy within much shorter ranges.

It is therefore vital to know the spatial distribution of both heat demands and potential sources for the production of heating when looking at the potential for district heating. The mapping of both demands and resources in the Pan-European Thermal Atlas 4 (Peta4) done in the HRE project provides this information for each of the 14 member states in the project [5].



The Pan-European Thermal Atlas (Peta) is an interactive map that can be used for district energy planning. For HRE, an updated version was created that models heat demands to the hectare level, and identifies continuous heat and cold demand areas that have potential for district energy. In addition, Peta spatially identifies (sustainable) resources like geothermal, solar thermal, excess heat, biomass, and heat for heating and cooling, and allows for efficient allocation to the local potential DH areas.

Peta4 for Finland provides geographically explicit information on heating and cooling as well as estimates on the cost of distributing district energy on a hectare level. It also provides information on specific potential excess heat facilities including theoretical excess heat availability and the specific location of the facility. Furthermore, it provides and overview of available local resources for heat production, namely for geothermal heat, biomass resources, and solar thermal district heating for smaller towns without excess heat resources.

When investigating the potential of district heating it is often beneficial to start in places with high heat demand densities. This is due to the nature of district heating networks, which decrease in cost per delivered energy unit when the distance travelled is reduced, similar to *e.g.* natural gas networks. The demand density is the driver of the infrastructure costs of a district heating network and is typically a result of local urban planning. The final extent of the district energy system is governed by the infrastructure costs, but also the availability of resources and energy system dynamics. This is why spatial planning must be combined with energy system analysis.

With the spatial explicit information on both heat and cold demand and potential resources for heat production a prioritisation of heat synergy regions has been made on a NUTS3 level for all of the 14 member states in the project. A very high priority is given to regions with high levels of both excess heat and heat demand and high priority is given to regions with moderate levels of excess heat and high heat demand. These types of regions are found in all 14 member states.

In Finland a total of 6 regions are assigned with the highest two priority levels. An example of a heat synergy region is Pohjois-Pohjanmaa. The city of Oulu has a total heat demand of 9,6 PJ, of which 5 PJ is located in areas with a heat demand density of more than 300 TJ/km^2. Within a distance of less than 4 kilometres from the centre of the city excess heat facilities with a theoretical output of more than 15,4 PJ are located, see Figure 2. This synergetic effect is based on the proximity of the cogeneration plants to the actual urban centre, rather than outside of the area.

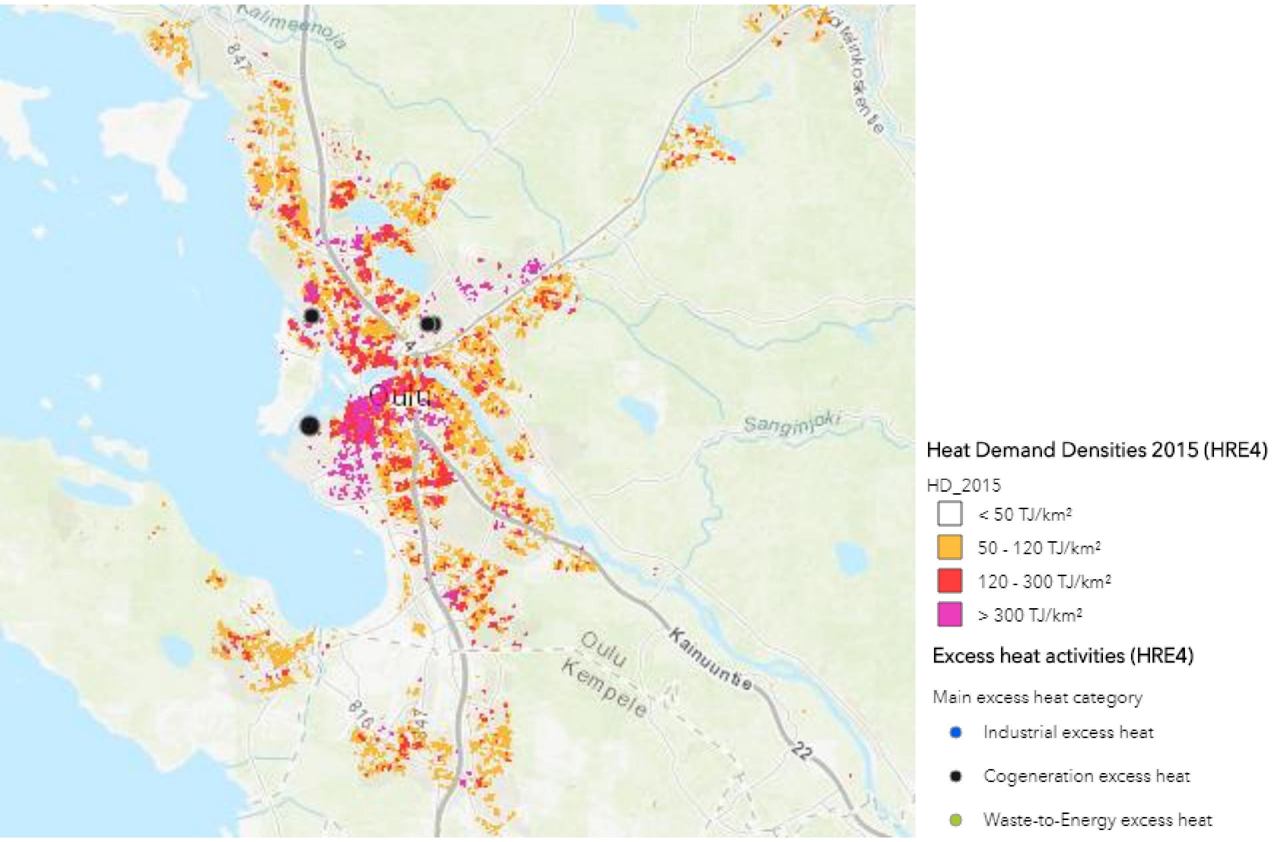


Figure 2. Heat demand density and excess heat activities Oulu.

Since the cost of the district heating pipes is dependent on the spatial distribution of the demands, cost curves are constructed in order to reflect this in terms of the potential. This is also important for other energy infrastructures like electricity and gas grids, but especially relevant for district heating and cooling since the infrastructure costs represent a larger part of the investment. The cost curves in HRE are made by aggregating hectare level demands, identifying coherent district heating areas and developing marginal cost curves. It is then possible to estimate shares of total national heat markets at different cost levels. For more information see Deliverable 2.3: *A final report outlining the methodology and assumption used in the mapping* [6]. The resulting district heating potential is dependent on climate, population density, urban planning and the built environment in the individual member states.

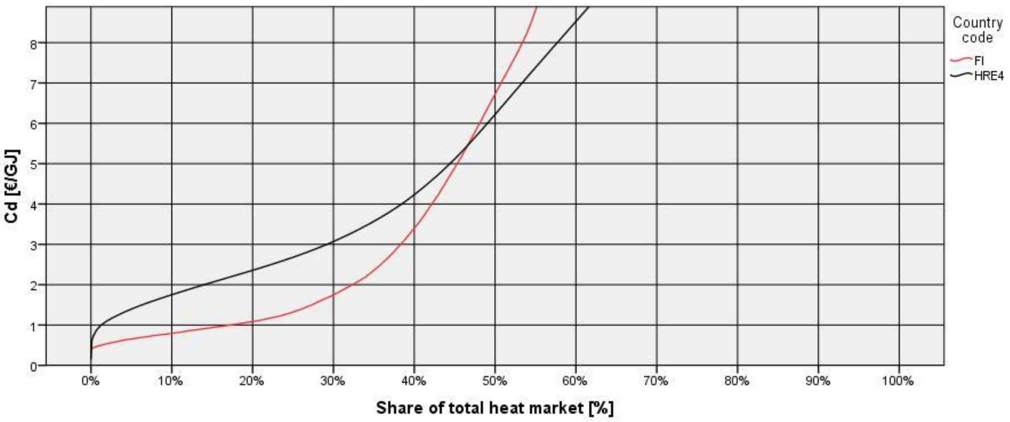


Figure 3. Distribution cost of heating at percentage share of total heat market for Finland and HRE average.

The cost curve, shown within the range of HRE countries and compared to the HRE average, is shown in Figure 3. The distribution costs for heating in Finland are, compared to the other HRE countries, low at market shares between 0% and 35%. Above 35% the marginal costs rise very rapidly. This indicates urban areas with a high heat demand density but less potential outside the urban centres. This may reflect the relatively high share of predominantly rural population in Finland.

Since density is affected not only by geography and climate, but also by urban planning and cultural practices, the outcomes of these maps and curves start to point towards discussions that are also relevant for transport and liveability planning. For example, the spatial energy planning can be driven by acceptable building heights, building/plot ratio guidelines, but also practices regarding aspirational living and rural living practices. This provides scope for further exploration at the local level, to understand the drivers behind the spatial nature of heat planning. For Finland, where the rural demand density is relatively low, this could be interesting to examine further in the more suburban and rural areas, especially given the potential to develop connection rates in some suburban areas.

Given the local nature of heating and cooling, it is not possible to ignore the geographically explicit distribution of both demands and possible supply sources. In order to make an analysis on a national level that respects the spatial constraints and particularities of thermal energy, it is necessary to base the cost of infrastructure and availability of resources in energy mapping. In addition, Peta4 allows for a starting point towards analysing and understanding the way that the energy system interacts with the planning of the built environment.

Heating and Cooling Demands

Currently, heating and cooling is the largest demand for energy in the Finland, comprising a full 60% of final energy demand (see Figure 4). This is higher than most European countries, where the figure lies around 50%. Of that, over half of that energy is used for space heating of buildings, with process heating (in industry and the service sector) representing the second largest demand. Cooling, both process and space heating, currently amounts to less than 4% of the heating and cooling demand, and as such does not represent a large part of the sector or energy system. However, it is also the sector with the greatest variability looking towards the future. This underwrites the idea that pathways towards a decarbonised energy system need to include an efficient, renewable heating and cooling sector, and that by their sheer scale, primary attention should be primarily given to space heating, which dominates the sector, and process heating, which includes the industry sector.

Finland has the fifth lowest final energy demand for heating and cooling among the HRE countries. Heating and cooling comprises 60% of Finland's final energy demand, with a very high need for space and process heating.

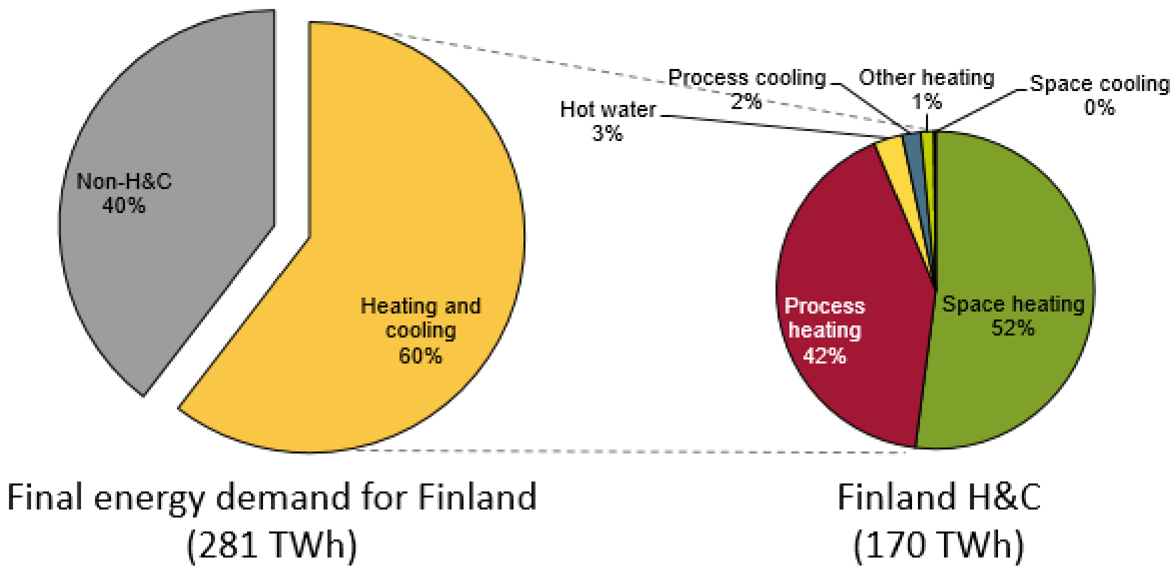


Figure 4: Heating and cooling demand in Finland by end-use compared to total final energy demand (2015 values).

Looking towards 2050, the current policy is ambitious regarding space heating, but overall does not reduce the energy demand for heating and cooling. On the contrary, the total energy demand is expected to increase by 3% (see Figure 5). This shows clearly the need to consider the increased efficiency of the heating and cooling sector in the form of reducing the energy demands for different types of heating and cooling, but also increasing the efficiency and renewability of the energy which is delivered. Energy efficiency on both the demand and the supply side are necessary and need to be combined to cost-effectively achieve decarbonisation goals for the heating and cooling sector.

Determining energy savings in Heat Roadmap Finland

The overall objective of Heat Roadmap Finland is to consider energy efficiency from both the demand and the supply side of the heating and cooling sector. Based on this perspective, the level of energy savings in Heat Roadmap Finland is determined by comparing increasing levels of additional delivered energy savings within the context of varying levels of (highly efficient) heat pumps and district energy. This approach represents a departure from previous Heat Roadmaps, where different levels of savings and different levels of heat supply were considered sequentially, but better describes the synergies and trade-offs between the two. Based on this analysis, a better balance between reducing energy demand and supplying (sustainable) energy efficiently can be made.

The matrix presented in Table 1 represents the results of this iterative simulation analysis. The iterations of district heating exclude areas where technical feasibility of district heating is challenging, and assume that the remainder of the heat demand is provided by (highly efficient) heat pumps. This also means that the top of the matrix, where no other type of heat supply is introduced, represent a fully electrified scenario for the heating supply system. The level of savings for the residential sector is considered in addition to the ambitious policy ambitions that currently exist.

The 60 simulations presented in this matrix are designed to be operational (in the sense that they can provide the energy demanded in every hour of the year), so they include the costs required for the electricity production for the heat pumps and supply technologies for the district heating systems. The district heating systems are generally supplied by the available renewables (between 5 and 10%), large heat pumps and cogeneration (around 30% each), around 25% of excess heat from industry and fuel production, and the remainder through boilers. In this way, the simulations are not fully optimised, but are designed to cover the full investment costs of all the generation and supply technologies that occur in the Heat Roadmap scenarios.

The results from the matrix for Finland show the balancing of increments of savings (on top of the current policy ambitions) with different ways to supply energy sustainably. One of the main observations from the matrices is that in terms of total energy system costs, the differences are not that great. It becomes clear that the sensitivities are relatively high, and there are various levels of district energy and energy savings that can contribute to the decarbonisation and increased competitiveness of the energy system. This sensitivity also means that there are various levels of district energy and energy savings that can contribute to the decarbonisation and increased competitiveness of the energy system.

Table 1. Total energy system costs: Relation between heat savings and supply

Total energy system costs (M€/year)		Residential sector space heating savings (additional to a 15% reduction already in the Baseline)					
		0	5%	10%	15%	20%	25%
Percentage of market share covered by DH	0%	51384	51406	51589	51854	52318	52422
	4%	51310	51330	51512	51776	52238	52340
	10%	51205	51224	51404	51666	52126	52227
	17%	51097	51114	51292	51552	52010	52110
	25%	50981	50996	51172	51431	51887	51985
	32%	50916	50930	51103	51361	51815	51911
	36%	50881	50893	51065	51321	51773	51867
	46%	50923	50934	51103	51358	51808	51900
	52%	51053	51062	51230	51482	51931	52022
	59%	51343	51350	51516	51767	52213	52303
	69%	53274	53280	53443	53693	54137	54225

In the case of district heating, implementing more than 50% of the technical potential (32% of the total heating and cooling market) leads to a slight increase of costs, which is why this is the level modelled in Heat Roadmap Finland. Nevertheless, the matrix shows that as much as 52% of the market share could be covered by district heating with very little extra cost.

For heat savings in the residential sector, the cut-off occurs between the current levels of heating savings and an additional 5% on top of the full implementation of current policy, which represents about a 19% reduction in space heating demands compared to 2015. Beyond this, the cost of implementing further savings does not pay off in comparison to the cost of supplying efficient and sustainable heat.

This analysis allows for the comparison of both various levels of heat pumps and district heating simultaneously, and limited increases in levels of savings, and a better analysis of the impact of energy efficiency on both the demand and the supply sector simultaneously, rather than sequentially. Based on this, a detailed analysis of the changes to the heating and cooling demands and the level of district energy in Heat Roadmap Finland can be developed.

Space heating

Space heating is, and remains in all scenarios, the largest demand in the thermal sector. However, policy regarding the energy performance of buildings has been extremely ambitious at both the European and the Finnish national level, so if current policy is fully implemented, this has an extremely large impact in terms of space heating, which decreases by 12 TWh in the 2050 Baseline. In Heat Roadmap Finland, a further 7%

reduction is recommended, in order to achieve both efficiency on the demand and the supply side of the heating and cooling sector.

This means that the challenge in terms of space heating does not lie in the level of the ambition of the current policy, but much more in its implementation and realisation. To achieve over a 20% reduction, both renovation rates and renovation depths have to be increased and the efficacy of the existing policies constantly monitored and reviewed. Without this, decarbonisation becomes both technically more limited (especially in rural areas) and is likely to come at a higher cost.

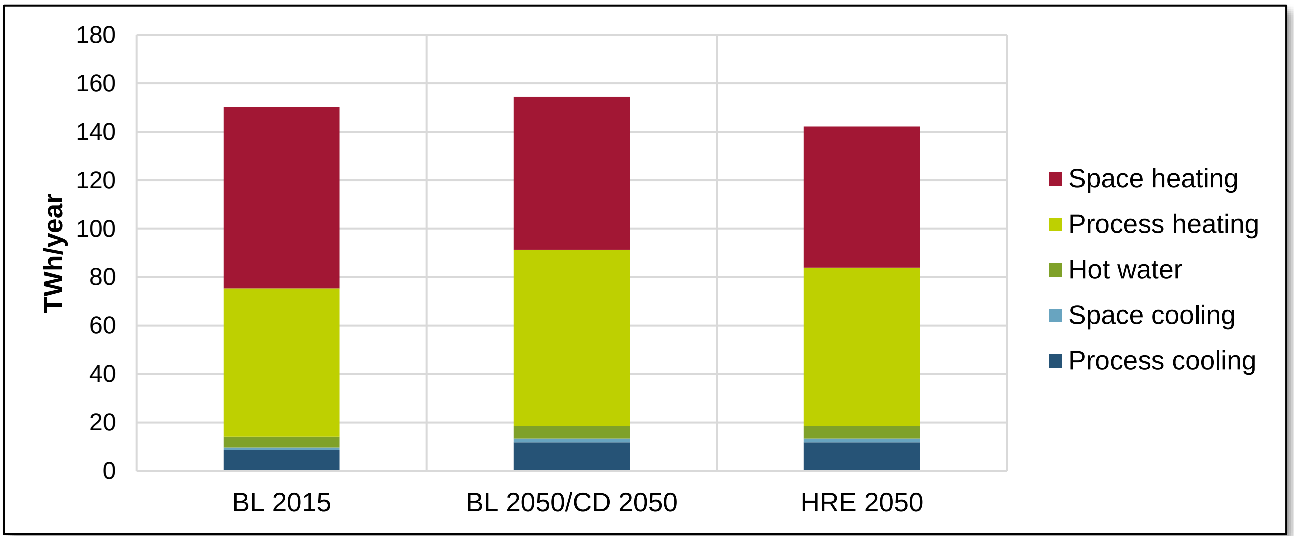


Figure 5. Delivered heating and cooling demands currently, and in the different scenarios.

Process heating and hot water demands

Process heating represents the second largest demand, the overwhelming majority of which is used by the industry sector in Finland. Since current policy has focussed mostly on space heating demands, under current policy savings in terms of process heating and hot water demands are not expected, and absolute demand for hot water and process heating will rise by around 19%. In this way, Heat Roadmap Finland shows that there is a lack of policies addressing savings in the remaining sectors, and that industrial heating demands need to be addressed in order to decarbonise the whole heating and cooling sector.

In terms of the potential for savings in process heating, additional measures are necessary since all possible considered savings beyond the current policy projections are socio-economically feasible and desirable. In Heat Roadmap Finland for 2050, that means that there should be savings of around 12%, in order to ensure the most cost-effective decarbonisation of the heating and cooling sector. Since these measures are in many ways more diverse than those for space heating (in many cases addressing different temperature levels in different industrial processes), the incentive framework needs to be carefully designed in order to capitalise on this potential.

Hot water demands represent around 4% of the thermal energy demand in Finland, meaning that while significant for the residential sector they do not represent a large part of the sector overall. Since demands are much more driven by behaviour and population, the ability to apply savings in this sector is relatively low and an overall growth of around 18% is expected between now and 2050 in the Heat Roadmap Finland scenario.

Cooling

Cooling, both in terms of space and process cooling, is the fastest growing part of the heating and cooling sector, but is not expected to represent more than 10% of the heating and cooling sector in Finland in 2050. Space cooling is expected have more than a 50% increase towards 2050 (from 0,9 to 1,5 TWh), the majority of which in the service sector (which includes among others offices, hospitals, schools, and commercial buildings). In terms of space cooling in the residential sector a twenty-five-fold increase is expected, but in absolute terms less than 8% of the 2050 demand is expected to be in the residential sector. At the same time, process cooling in industry is also expected to increase by around 30%, representing around 3% of the total heating and cooling demand in Heat Roadmap Finland. This means that while the growth for demand is very high (especially compared to space heating, where extremely substantial reductions in demand are considered for 2050), the heating and cooling sector overall is still dominated by space and process heating.

In addition, cooling is also typically produced very efficiently, so the potential for savings is not very high. No additional level of demand reductions (other than passive measures), either for space or process cooling, is considered to be socio-economically viable at a system level when compared to the investment costs of implementing such savings. However, those prospects are to be considered with (slightly) lower confidence level than those for heating, so further work is needed, especially to further explore how heat savings interact with increased cooling demands.

Heating and Cooling Supply in the Energy System

Integrated energy system approach in Heat Roadmap Finland

One of the main objectives in Heat Roadmap Finland is to consider the effects of a deeper interconnection of the heating and cooling sector with the other parts of the energy system, creating synergies that result in a better use of the resources that are available, a lower level of cost and fuel use, and deeper decarbonisation (see Figure 6). The synergy between the heating and cooling sectors and the industry (including the electrofuel production industry) is considered primarily from the perspective of being able to recover the excess heat that is lost within the conversion processes in thermal networks. This heat, which would otherwise be lost, can then be used to replace the use of other resources for the production of heating and cooling.

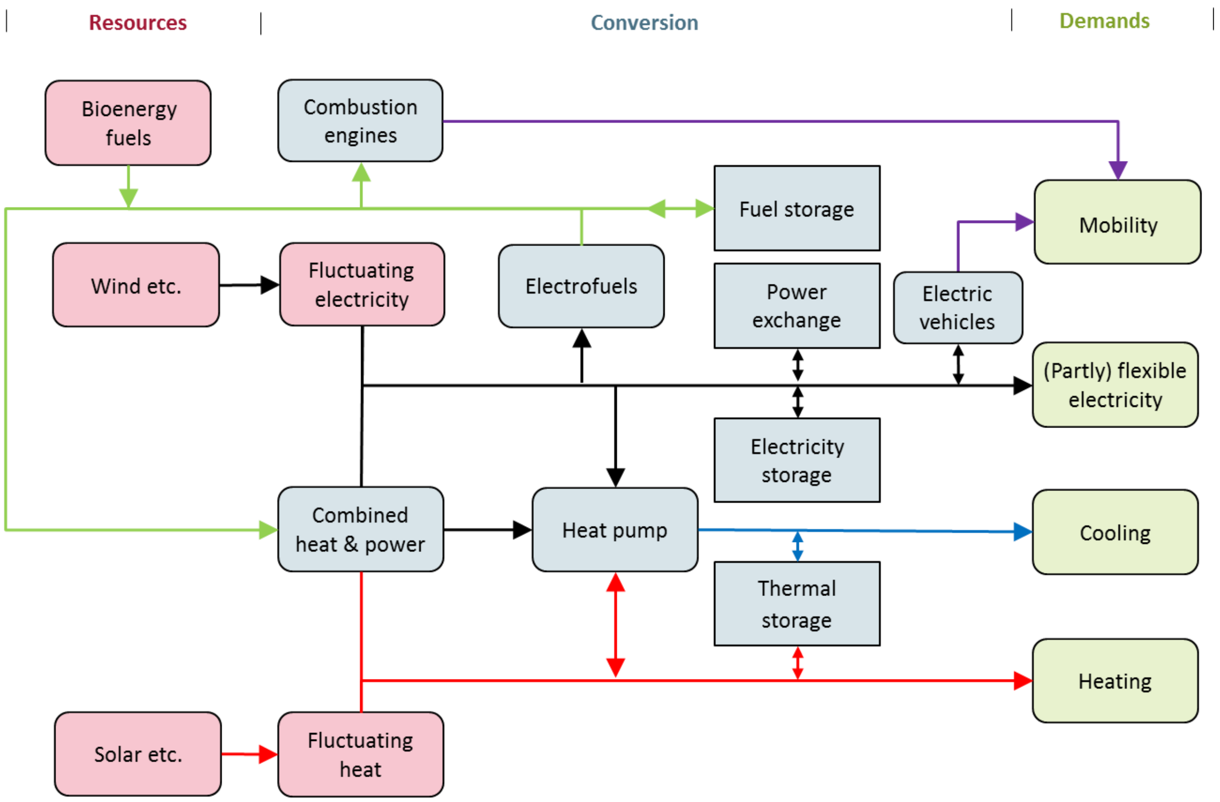


Figure 6. Illustration of the interconnected sectors, heating and cooling included, of a Smart Energy System.

The heating and cooling sector in Heat Roadmap Finland is also connected more deeply with the electricity sector through the use of combined heat and power and heat pumps. The use of cogeneration, which responds to electricity demands but creates heat as a by-product, reduces the need for resource use in the heating and cooling sector in a similar way to the recovery of excess heat from industry. In addition, combined heat and power units are operationally more responsive than large condensing plants, so can respond better to the temporal fluctuations in variable renewable energy sources, allowing for more effective use of wind and solar power. Heat pumps can further contribute to this effect, providing heat in a highly efficient manner when electricity is abundant, potentially converting it into storage, and in this way reducing critical excess electricity and resulting in a better integration of variable renewable energy sources.

Through this, Heat Roadmap Finland represents a technically feasible and economically viable alternative to other reference and decarbonisation scenarios, which could contribute to the deep decarbonisation of the Finnish energy system. It is precautionary in approach, since the technologies and resources used in Heat Roadmap Finland are proven and already widely used. Efficiency and decarbonisation are then achieved by considering both a demand and a supply perspective of the heating and cooling sector, and using an integrated perspective utilising the synergies between the heating and cooling and other sectors to achieve efficiency and a higher level of renewable integration

District heating in urban areas

The costs of implementing district energy and the resources available to the district energy systems are based on spatial modelling. This is done in order to a) better understand the local nature of both thermal demands and resources, and b) to account for the infrastructure costs and losses that are necessary to transport thermal energy. The optimal level is identified using same iterative modelling described to determine the optimal level for energy savings.

The level of district heating retained from the modelling was slightly lower than the currently high share of 48%. This reduction is mainly driven by the relatively high share of predominantly rural population in Finland, and less district heating potential outside urban centres with high heat demand density, considered in the spatial modelling. However, from an economic perspective, Heat Roadmap Finland shows that the district heating share could be as high as 52% (excluding DH for industry).

The district heating sector is designed so that it uses no fossil fuels directly, in order to fully decarbonise the sector. Not using the excess heat sources from industry and cogeneration (which may still include some fossil fuels, even in a deeply decarbonised energy system) ignores the potential to recover energy already used in industry and power generation, limiting the overall efficiency of the system and possibility of coupling the electricity and heating sector. The main sources for heat are large scale heat pumps and cogeneration (supplying around 36% and 41%, respectively), with large shares for excess heat from various industrial activities (see Figure 7). Geothermal and large scale solar thermal are also used, with heat only boilers producing less than 8% of the district heating supply.

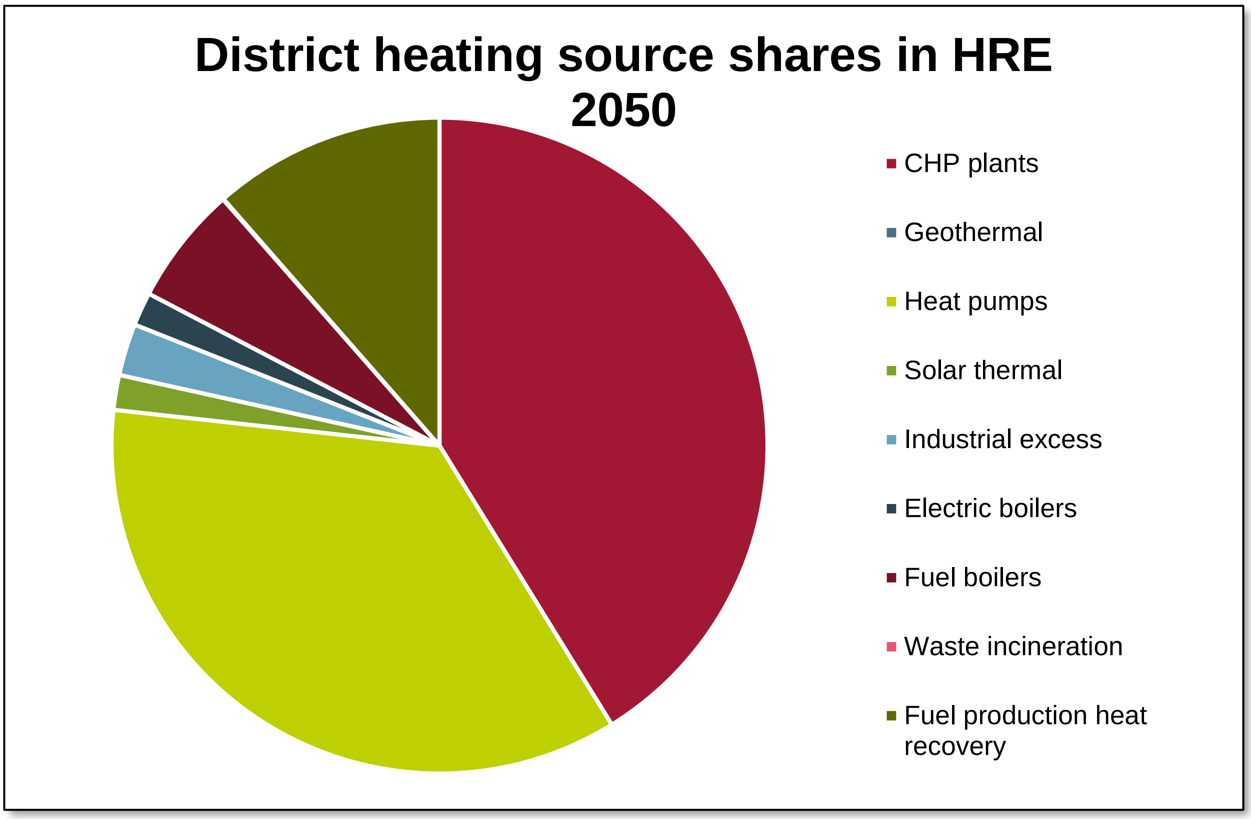


Figure 7. Heat sources for district heating in Heat Roadmap Finland.

Excess heat recovery

One of the main ways in which Heat Roadmap Finland creates synergies between the heating and cooling and other energy sectors, is by using excess heat from industrial processes for the district heating system. In Heat Roadmap Finland, the potential to operationally excess heat from industry is bounded geographically, temporally, and by temperature. The level of district heating in Heat Roadmap Finland has been designed assuming excess heat can be used only to cover the baseload and that which exists currently must be spatially present within a 50 kilometre zone of the prospective district heating system, and be within temperature. These boundaries are intended to create the distinction between the theoretical excess heat potential (i.e. all heat which is lost in industrial processes) and the accessible heat potential, which is a more realistic consideration of how heat can be used in district heating systems. Because excess heat is effectively the cheapest form of heat, that is in some ways limiting. Further research is needed to understand the role of non-baseload excess heat, especially in smaller district heating networks.

The excess heat sources considered in Heat Roadmap Finland are comprised of a variety of different types, including waste-to-energy and industrial sources like chemical and steel manufacturing. Respectively, these amount to less than 1% and 3% of the total district heating production. However, within a deeply decarbonised energy system where a variety of hydrogen and electrofuels are produced, additional types of excess heat become available. In Heat Roadmap Finland, a 10% heat recovery share of fuel production also becomes a significant source of industrial excess heat (representing around 11% of the district heating production), assuming that they can be located within the 50 kilometre zones of prospective district heating areas. By using a wide variety of different types of excess heat sources (both on a national and on a local level), a resilience can be designed into the scenario, reducing the dependence on one specific type of industrial activity or plant in the region, and to a certain extent safeguarding the safety of supply.

The modelling of the HRE 2050 scenario included several sensitivity analyses where excess heat from industry was excluded. In these scenarios, district heating was still viable. However, scenarios without excess heat available to the district heating system typically have a slightly reduced market share since the relative efficiency of individual solution (particularly heat pumps) increased. Due to this, the spatial availability of renewables (particularly large scale solar thermal) is also lower. These scenarios replace the excess heat from industry with a higher use of large scale heat pumps, slightly higher CHP levels, and a more than doubling of direct boiler usage. Therefore, while district heating is still a viable solution in cases where excess heat is not recovered, these systems overall are more expensive, have significantly more difficulties integrating variable intermittent renewable electricity sources, and require more biomass.

Renewable heat sources

The potential for renewables in the district heating supply mix is mostly geographically determined. For large scale solar thermal and geothermal this is especially the case, since their potential is likely to be highest in smaller, more decentralised district heating systems where no excess heat is available. Geothermal potentials are especially hard to quantify spatially in terms of how much would be accessible for use based on the extent of the district heating penetration (see Deliverable 2.3 [6]). Because of this, fairly conservative assumptions were used in the allocation analysis for geothermal.

The potential in Finland for geothermal using this methodology is rather limited, representing a negligible fraction of the district heating supply. Operationally, it could be used as a baseload supply (with some being redirected into storage during the summer), with very little temporal changes throughout the year. In addition, all the available geothermal potential that exists is economically viable, indicating that if the potential is there, the option of geothermal may be relevant even in larger systems where other types of baseload heat supply may be present. This means that where possible, geothermal energy in district heating presents a good solution to increase the share of renewables, reduce CO_2, and lower the fuel consumption in a cost-effective manner.

Solar thermal plays is expected to play a slightly larger role in Finland, making up around 2% of the district heating supply. However, compared to the technically available potential, this does not represent the full amount of large scale solar thermal that could be utilised. In Heat Roadmap Finland, solar thermal in district heating is mainly envisaged in the smaller district heating systems, where there is no opportunity to use excess heat, cogeneration, or geothermal sources as an effective baseload production.

This is primarily because of the temporal discordance between when heat is demanded, when it requires storage, and the competition between the other available baseload heat supply options (mainly excess heat from industries, and geothermal where available). Further research, which can make a more refined differentiation between the available heat sources for individual prospective district heating systems, is likely to show a different result, if it can represent at a more disaggregated level how much of the district heating demand cannot be connected to excess heat from (baseload) industries and geothermal. This is in line with other research showcasing the role of solar thermal in European energy systems, which concluded that the potential is normally between 3% and 10% of the heat production, and is mostly relevant as a source of sustainable heat where there is no possibility of using alternative (baseload) heat sources [7].

Large scale heat pumps and cogeneration

Large scale heat pumps play a very large role in the supply of the district heating supply in Heat Roadmap Finland. In total, they supply over 35% of the total district heating demand. This is because they can provide heat in a highly efficient manner, and provide a valuable link with the electricity sector through their use of (variable) renewable resources. Operationally, this means that they mostly function flexibly, in hours of the year when wind and solar electricity is abundant, thereby integrating renewable electricity into the heating and cooling sector. This also allows for filling of the large thermal storages, allowing for even further use of the variable renewables. Based on this, large scale heat pumps have the potential to be an important technology in the heating and cooling sector in the long run, both in terms of scale and in terms of enabling variable renewable electricity utilisation. The deployment of large scale heat pumps needs to become a key element of the (re-)development of district heating systems in Finland.

The applications modelled in Heat Roadmap Finland largely represent traditional applications of heat pumps in district heating systems, as they are common in some European countries today [8]. However, they are also modelled within the framework of a complete phase-out of HFC refrigerants, which means that the coefficient of performance (COP) of the large scale heat pumps lies around 4. There may be technical potential to expand this, as a better understanding is generated of their applicability in unconventional heat sources, which could raise the COP significantly. This may on the one hand lead to a larger share of heat being produced by heat pumps, and a decreased capacity (accompanied by a decrease in capacity cost) required. Further research, particularly on the cost-effective role of storage in such scenarios, is necessary to understand better how radically increased efficiencies would work in the district heating sector.

The second link with the electricity sector is represented in the use of cogeneration, which produces around 41% of the redesigned district heating supply in Finland. This is both less than the heat which is being produced in CHPs in 2015, and less than it would be in a conventionally decarbonised scenario. This reduction in Heat Roadmap Finland is partially due to the integration of renewable and excess heat sources, but primarily due to the increased use of (large scale) heat pumps, which allow for more flexibility in the electricity system and reduce the overall demand for electricity. While the heat from cogeneration is considered by-product, the fuel used in CHPs in Heat Roadmap Finland is biomass. This means that the reduced level of CHP also results in eliminating the indirect combustion of fossil fuels and further decarbonises the wider energy system.

In terms of regulation, the heat from CHPs can be considered a by-product because these CHP units follow the electricity market, and the heat produced is considered secondary. When heat storages have been filled and heat demand is low, electricity demand is typically fulfilled by power plants, showing that the CHPs are not operating to fulfil the heat demand, but are a way of using the heat as a by-product to electricity operation. In order to do this, it is both necessary to have a wider variety of heat sources in the district heating systems that can displace the cogeneration when electricity is abundant, but also to have a flexible electricity regulations. In this regard, the combination between cogeneration, heat pumps, and storage works extremely well in terms of the district heating system being able to respond to both high and low electricity availability hours and both high and low heat demand hours. In this way, the redesigned heating and cooling system, using cogeneration, allows for a high level of efficiency by using the by-product of electricity generation and provides a key link and synergy with the electricity sector.

This can also be seen from the sensitivity analyses which were done on the HRE 2050 scenario, where cogeneration was reduced and then excluded from the heat and electricity supply mix. As with the sensitivity analyses with excess heat, the potential for expansion of the district heating sector (and therefore the geographic accessibility to geothermal and peripheral solar thermal) is slightly reduced. However, the main changes in the supply of the district heating sector are in the use of heat pumps (for which the capacity is now using electricity, partially provided through condensation power plants, to produce heat) and the almost seven-fold increase of heat produced by heat-only boilers. In addition, the CHP capacity that was removed is almost fully transferred into condensation power plants, showing that both the regulation and the capacity of CHPs is much more driven by the needs of the electricity sector than of the district heating systems.

While district heating remains both economically viable, without cogeneration, these overall energy system is more expensive, has significantly more difficulties integrating variable intermittent renewable electricity sources, requires more electric capacity and requires either more fossil fuels or an unsustainable level of biomass. Based on this, the role of cogeneration in future district heating systems needs to be understood as more deeply engrained in the electricity sector than it currently is.

The Heat Roadmap Finland scenario shows a district heating sector looking towards 2050 which has a large variety of heat sources; uses both renewable, highly efficient, and excess sources of heat; and creates a strong link to the electricity sector, allowing for not only the decarbonisation of the district heating sector itself but also further integration of renewable electricity into the wider energy system. As the supply and supply sources for district heating become more efficient and varied, the marginal costs of supplying heat fall, creating much more competition within the baseloads of district heating system markets, since the majority of these technologies are more socio-economically viable with high operating hours. For this reason, a better understanding of the exact shares of particularly excess heat and solar thermal energy would benefit from an approach that can both consider the spatial allocation of these sources, but also represent a better distinction between large, multi-source district heating systems and smaller district heating networks which are not likely to have more than two or three main heat sources.

Individual heating supply

Where network solutions are not viable and individual supply options are more cost-effective than district energy, heat pumps are used to supply the remaining heat demands. Biomass boilers, electric heating, solar thermal, and heat pumps are considered, but heat pumps demonstrate the distinct advantage of efficiency and integration with the electricity sector. In addition, due to the decarbonisation of transport and (high-temperature) industry, bioenergy becomes increasingly scarce and its use in biomass boilers uneconomical from a system perspective.

In the Heat Roadmap scenario, individual heat pumps provide almost all the remaining heating demand in Finland, covering almost 53% of the heating sector. This is primarily in the rural and highly suburban areas, and a relatively high market share compared to the HRE 2050 average for the 14 HRE4 countries. Especially compared to 2015, this means both a reduction in the amount of individual heat that is required, and an almost full replacement of the individual boilers, which are currently mostly fuelled by gas (Figure 8). This allows for a much higher level of efficiency, and a deeper level of decarbonisation through a deeper interconnection with the electricity sector.

The heat pumps considered in Heat Roadmap Finland are primarily ground-source heat pumps, air-to-air heat pumps, and air-to-water heat pumps with a high level of efficiency and the ability to produce both space heating and hot water. The high COPs of the individual heat pumps, which averages 3,5 overall, results in a very low energy consumption and minimises the consumption of biomass, significantly contributing to the decarbonisation of the remaining heat demand.

However, the increased demand of electricity for heat pumps is visible in increased electricity demand, but also in the peak electricity load. For Finland, this amounts to around 2.608 MW additional peak electricity capacity, which represents around 2% of the total electricity capacity. In terms of electricity grid infrastructure, the expansion requires approximately 493 million euros worth of additional grid capacity. These are non-negligible amounts, and illustrate the need for high COPs. Nevertheless, the main costs associated with supplying heat at the individual building level is the investment required for the heat pumps themselves.

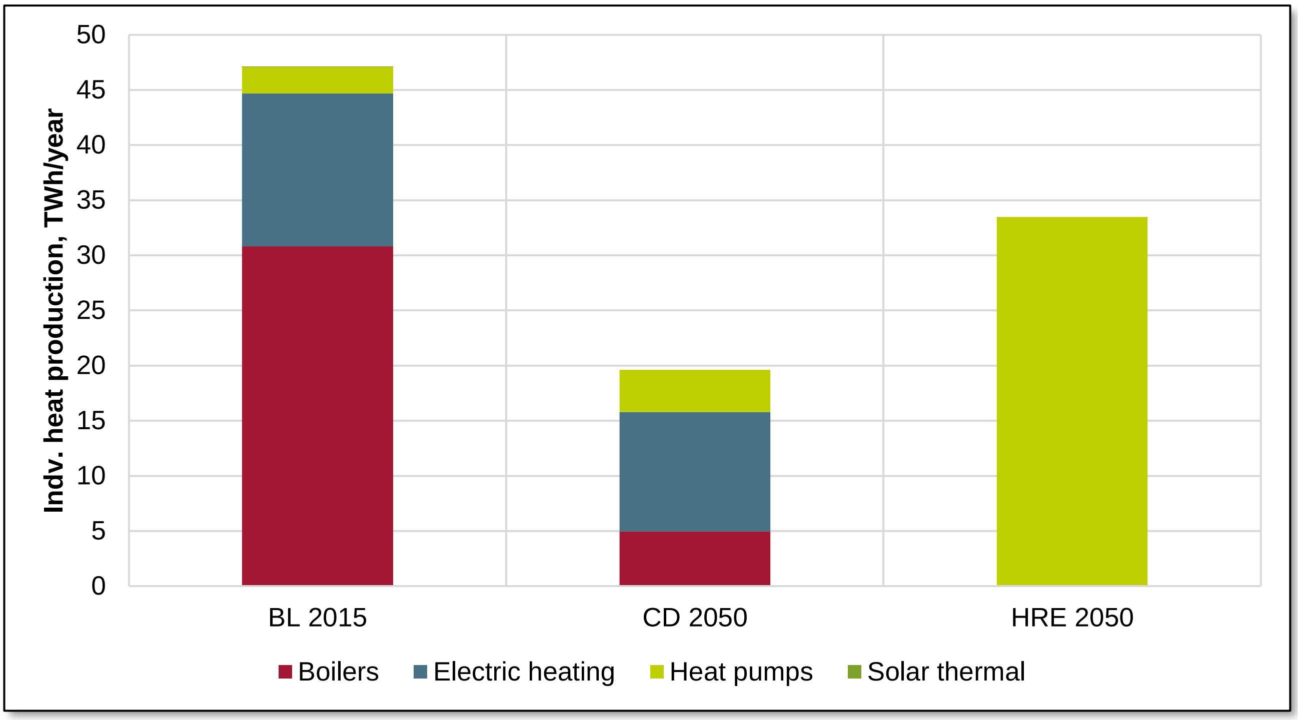


Figure 8. Heat sources for individual heat production in Finland for the three scenarios.

The electricity that is used for heat pumps generally reflects the supply mix of the electricity sector, and includes a high level of variable renewables; shares of biomass combustion (in both cogeneration and condensing power plants), and a small amount of remaining fossil fuels. However, heat pumps are the primary way of supplying highly efficient and decarbonised heating in areas where district heating networks are not cost-effective, and contribute both to the overall efficiency and the decarbonisation of the energy system in Heat Roadmap Finland.

Cooling supply

Cooling is considered in Heat Roadmap Finland in a similar way as heating; through spatial analysis of the demands and resources, and scenario development considering both district and individual supply options. However, the cooling sector is more diverse than the heating sector. Furthermore, cooling is mostly demanded by the industry and service sector, meaning that both determining the spatial demands and the nature of centralised and decentralised supply are slightly different.

District cooling is implemented in 20% of the urban areas in Finland, resulting in an overall market share of less than 1% of the cooling market. However, the spatial analysis and energy system modelling that lead to this result are not as methodologically robust as those for the heating market. This is likely to be an underestimation, since the spatial dimensions of top-down cooling network modelling is not as well developed as for district heating infrastructures. In terms of operational simulation, district cooling is supplied equally through sorption cooling (using excess heat from the district heating system) and centralised chillers. The potential to explore the role of using direct sea- and lake water (where geographically available) and higher levels of cold water thermal storage requires further investigation to be able to fully understand the potential and role that district solutions for cooling could play.

The individual cooling demand is supplied using mostly (small) split units, large split units, and chillers of varying sizes. Cooling is one of the fastest growing of the thermal sectors, but supply options can be highly efficient, with COPs ambitiously expected to be around 6,6 in 2050. This is also the case in Heat Roadmap Finland, where approximately 2 TWh of electricity is used for cooling. This high efficiency, combined with the relatively smaller demands than for the cooling sector, is the main reason that even as the cooling sector expands, the impact on the wider energy system is relatively limited.

Integrating renewables into the electricity sector

One of the key objectives of HRE4 is to understand the effects of a deeper interconnection of the heating and cooling sector with the other parts of the energy system, in particular creating synergies with the electricity sector that result in a better use of the resources that are available. In particular, the way that the electricity sector is redesigned is highly complementary to the design of the heating and cooling system; both to balance the operation, and to ensure that the synergies that are created through the heating and cooling sector are realised.

In order to do this, the transport and (non-heat) industry sectors are taken over from a conventionally decarbonised scenario, in order to account for the electricity and fuel demands of these sectors. Since these sectors do not form the main subject of analysis in these Heat Roadmaps, they are not analysed in depth but they are taken into consideration in order to ensure the results could contribute to a fully decarbonised energy system. This is particularly important with regard to the electricity demand which comes from the electrification of transport, the production of hydrogen and electrofuels (to replace fossil fuels where direct electrification is not possible), and strategic use of bioenergy. By including these into the energy system, and considering the effect of the measures taken in Heat Roadmap Finland on an energy system level, an analysis can be made on the synergies between decarbonising the heating and cooling sector and the electricity sector.

Compared to a conventionally decarbonised energy system, the increased level of energy efficiency in the heating and cooling sector also means less demand for the electrification of the heating and cooling sector (see Figure 9). The overall electricity production in both the conventionally decarbonised and Heat Roadmap scenario are much higher, since there is a very high level of electrification in the transport and industry sectors, and power is being used for electrofuel production. However, the overall need for electricity production in Heat Roadmap Finland compared to a conventionally decarbonised energy system is reduced by over 7%, simply because electricity demand for heating and cooling is replaced by district solutions, which can integrate more types of energy sources. Of this decrease in electricity production, the majority is in cogeneration (despite the increase in district heating) and condensing power plants, with only a minor decrease in the amount of variable renewable energy produced. Proportionally, this means that the variable electricity which is being produced in the Heat Roadmap scenario is being integrated at a higher level, indicating a higher level of flexibility within the system.

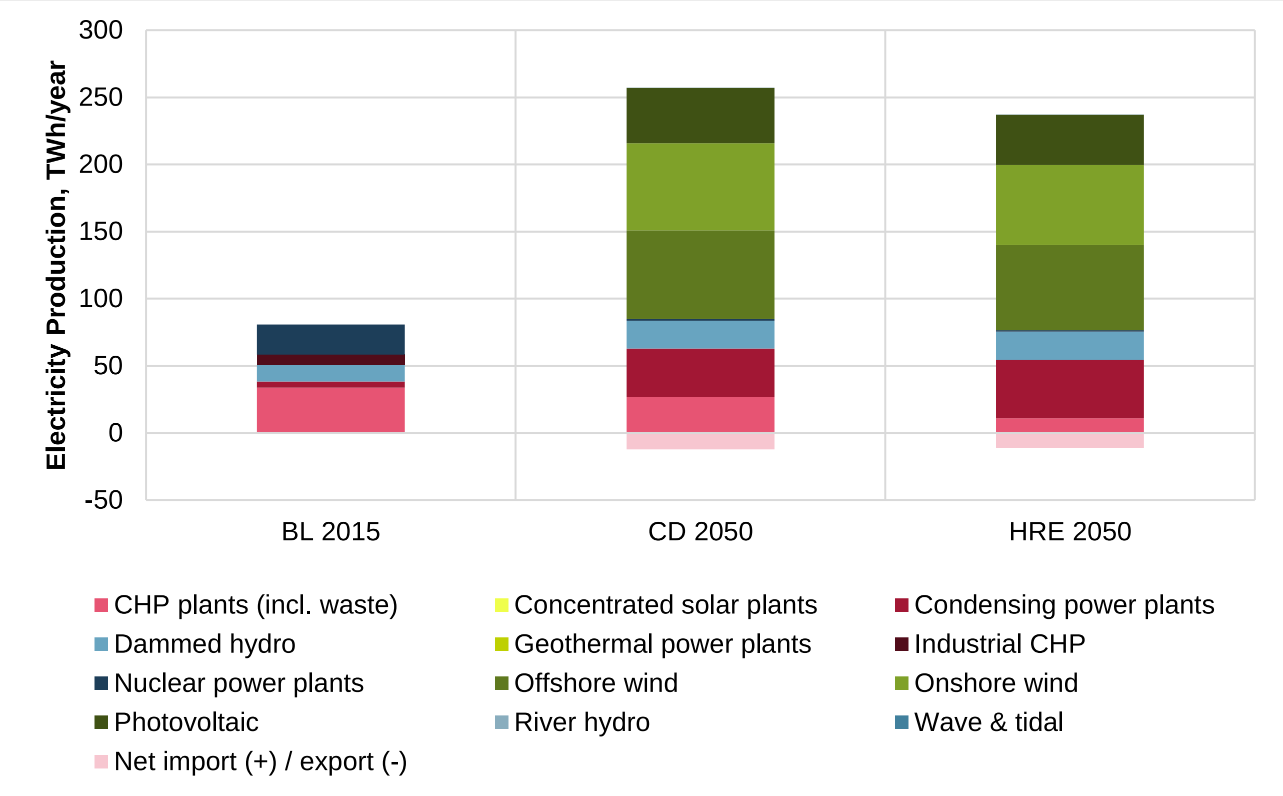


Figure 9. Energy conversion technologies for electricity production in the three scenarios.

In terms of electricity production, the majority of electricity in the Heat Roadmap Finland scenario is produced by offshore and onshore wind, each representing about a quarter of the electricity produced. The second largest sources are condensing power plants and photovoltaic, producing around 18% and 16%, respectively. Combined heat and power plants produce an additional 5% of the electricity demand, which is marginally higher than the HRE 2050 average for the 14 HRE4 countries. Run of the river and dammed hydro combined produce approximately an additional 9% of the electricity demand in Finland.

The condensing power plants are the main consumers of biomass in the Heat Roadmap Finland scenario, and show that a while redesign of the heating and cooling sector does contribute to the deep decarbonisation and efficiency of the energy system, further measures (better linking the transport, fuel production and other energy sectors) could contribute to an even more efficient energy system. However, the redesign of the heating and cooling system using principles in line with the Smart Energy System approach already allow for a more efficient power sector, better integration of variable renewables, and a much deeper level of decarbonisation.

Final Heat Roadmap Results

The main aim of the Heat Roadmap scenarios is to demonstrate and understand how to cost-effectively use energy efficiency, be decarbonised, and to redesign a heating and cooling that fits within a broader decarbonised The Heat Roadmap Finland scenario covers the heating, cooling, industry, electricity and transport sector, but in the analysis focus is primarily on what can be achieved in the heating, cooling, industry, and power sector.

The resulting Heat Roadmap for Finland represents a technically feasible, economically viable alternative which shows how the heating and cooling sector could provide a large contribution to the deep decarbonisation of the Finnish energy system. The approach is based on the combination of energy efficiency on the demand and the supply side of the heating and cooling sector, as a way to achieve a higher level of every savings in the system overall. Savings for both heating and cooling demand are considered simultaneous to an efficient supply of heating and cooling through heat pumps, efficient chillers, and district solutions, and combined with a high level of system integration and variable renewable sources.

Decarbonisation

Heat Roadmap Finland shows that deeper decarbonisation, moving towards a nearly zero carbon emission energy system, is possible. Within the context of the HRE project, 'deep decarbonisation' is taken to mean a moving towards a 95% reduction in CO_2 emissions by 2050, compared to 1990 levels. The conventionally decarbonised energy system represents an 94% decrease compared to 1990 (in line with the current long-term goal of between 80% and 95% [9]), while the Heat Roadmaps aim for a level which is more in line with deep decarbonisation and eventual carbon-negative energy systems.

Heat Roadmap Finland reduces energy-related emissions by 56% compared to conventional decarbonisation, and the overall net emissions by 103% compared to 1990 levels when accounting for carbon sinks in non-energy sectors (see Figure 10).This level of decarbonisation is especially remarkable since in the Heat Roadmap scenario the transport and non-heating/cooling industry sectors were taken as given from a conventionally decarbonisation is especially remarkable since in the scenario the transport and non-heating/cooling industry sectors were taken as given from a conventionally decarbonised scenario, and changes were made primarily in the heating and cooling, and to a lesser degree the electricity sector. With further integration of the sectors, higher levels of decarbonisation can be expected.

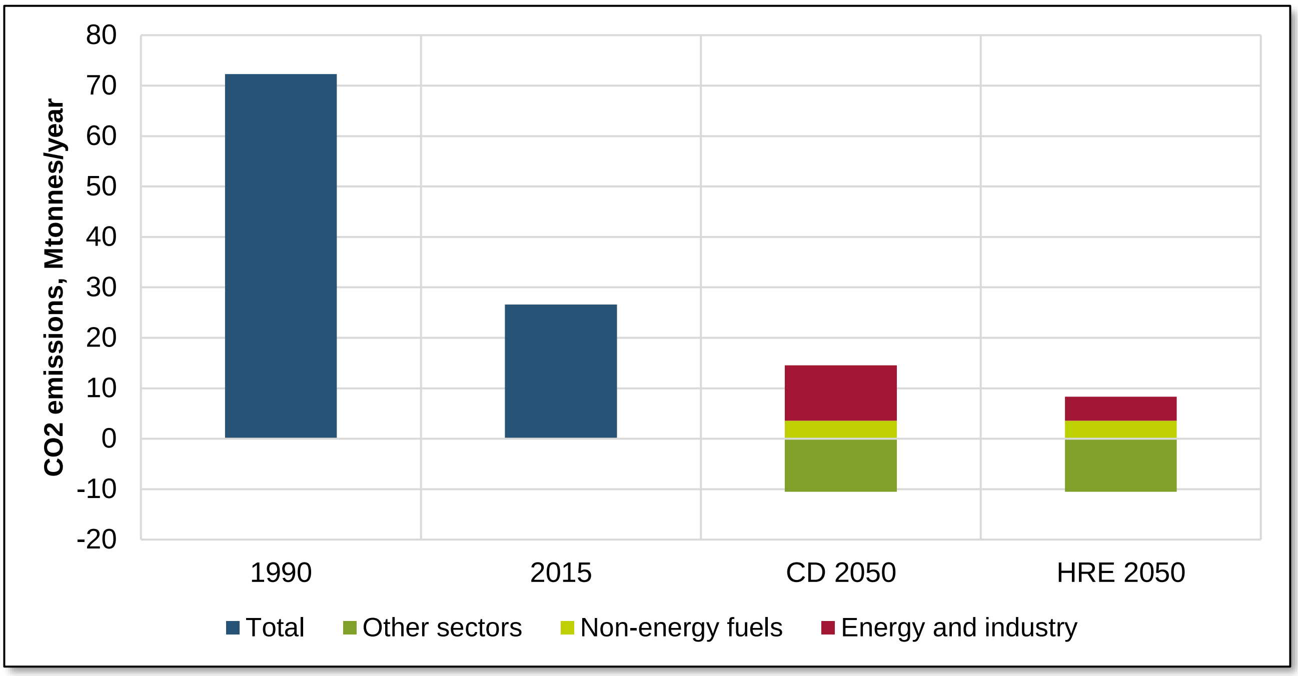


Figure 10. CO2 emissions for Finland (including 1990, the base year for the Paris Agreement), currently, in a conventionally decarbonised scenario, and the Heat Roadmap scenario.

Efficiency

In terms of primary energy supply, the Heat Roadmap Finland uses approximately 16% less energy than a conventionally decarbonised energy system. This is due to the near elimination of natural gas and oil as fuels, as well as a decrease of biomass, while the main renewables (wind and solar for Finland) are relatively comparable (see Figure 11). While most of this gas was being used in the electricity sector, its use can be displaced through higher levels of efficiency in the heating and cooling sector.

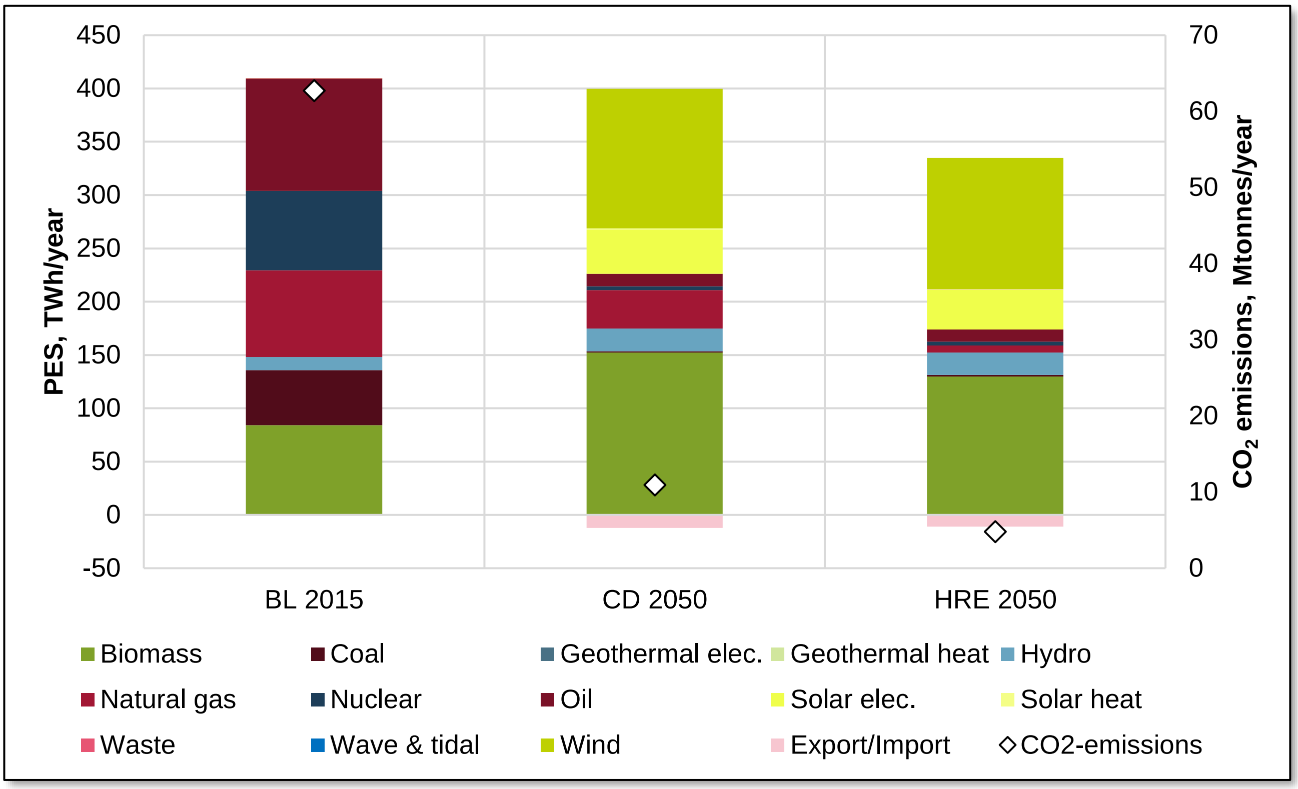


Figure 11. Primary energy supply and sources with respective CO2 emissions for the three scenarios.

This primary energy reduction is partially brought through heat savings measures, and partially by efficiency in the demand side through the integration of excess heat sources, use of efficient supply technologies, and the better integration of the heating and cooling sector with the electricity sector. When split between the two, of this decrease in energy needs almost 28% is driven by the end user savings in the built environment with the remaining 72%. This underlines the importance of focussing not only on heat and cold savings, but also the need energy efficiency on both sides, in order to have a more cost-effective and deeply decarbonised energy system

Economy

The HRE 2050 scenario achieves a deeper level of decarbonisation and a higher efficiency at a reduced cost, compared to a conventionally decarbonised scenario. The annual cost of achieving the energy system simulated in Heat Roadmap Finland is around 5% lower than the decarbonised energy system, equalling cost savings of around €1,5 billion annually (see Figure 12). While investments increase slightly, this cost reduction is made through a shift away from using fuels and in that a significant reduction of fuel costs.

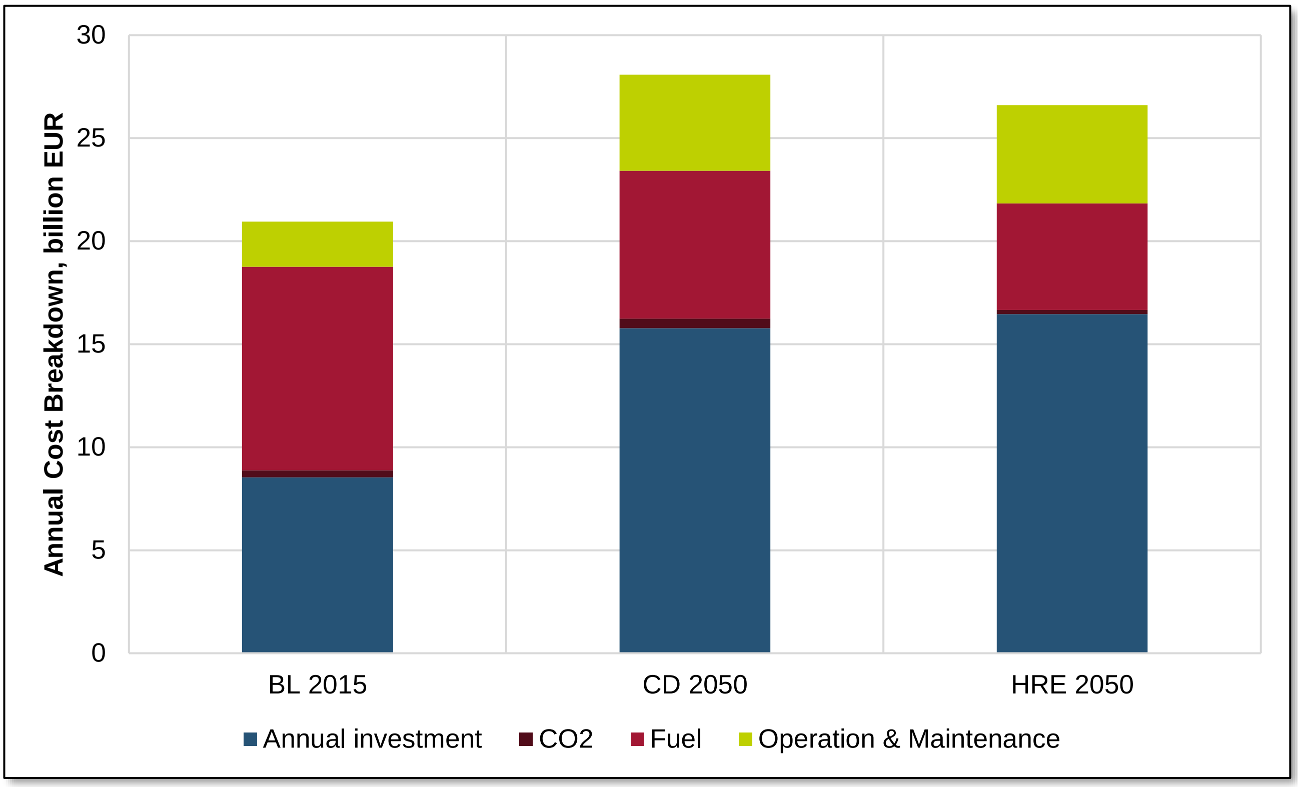


Figure 12. Annual socio-economic costs for the heating, cooling, electricity, industry, and transport sector for Finland.

There are some changes in terms of investment that are required in a Heat Roadmap Finland scenario, compared to today and a conventionally decarbonised energy system. The overwhelming category of investments needed in Finland is in heat demand reduction measures, which make up almost two thirds of the investments required in the heating sector and almost as much as for the entire electricity sector. The scale of these investments needed shows the required ambition of the policies regarding heat savings, but also the need for a much stronger focus and enhanced approach towards policy implementation and realisation on a country level.

These costs are annualised and include the replacement of existing technologies. In terms of the investment in the energy system outside of the built environment, the highest levels of new investment are needed in the electricity sector, in order to facilitate the transition towards variable renewables and the partial electrification of other sectors (see Figure 13). There are however also some changes to the investments necessary in the heating and cooling sector.

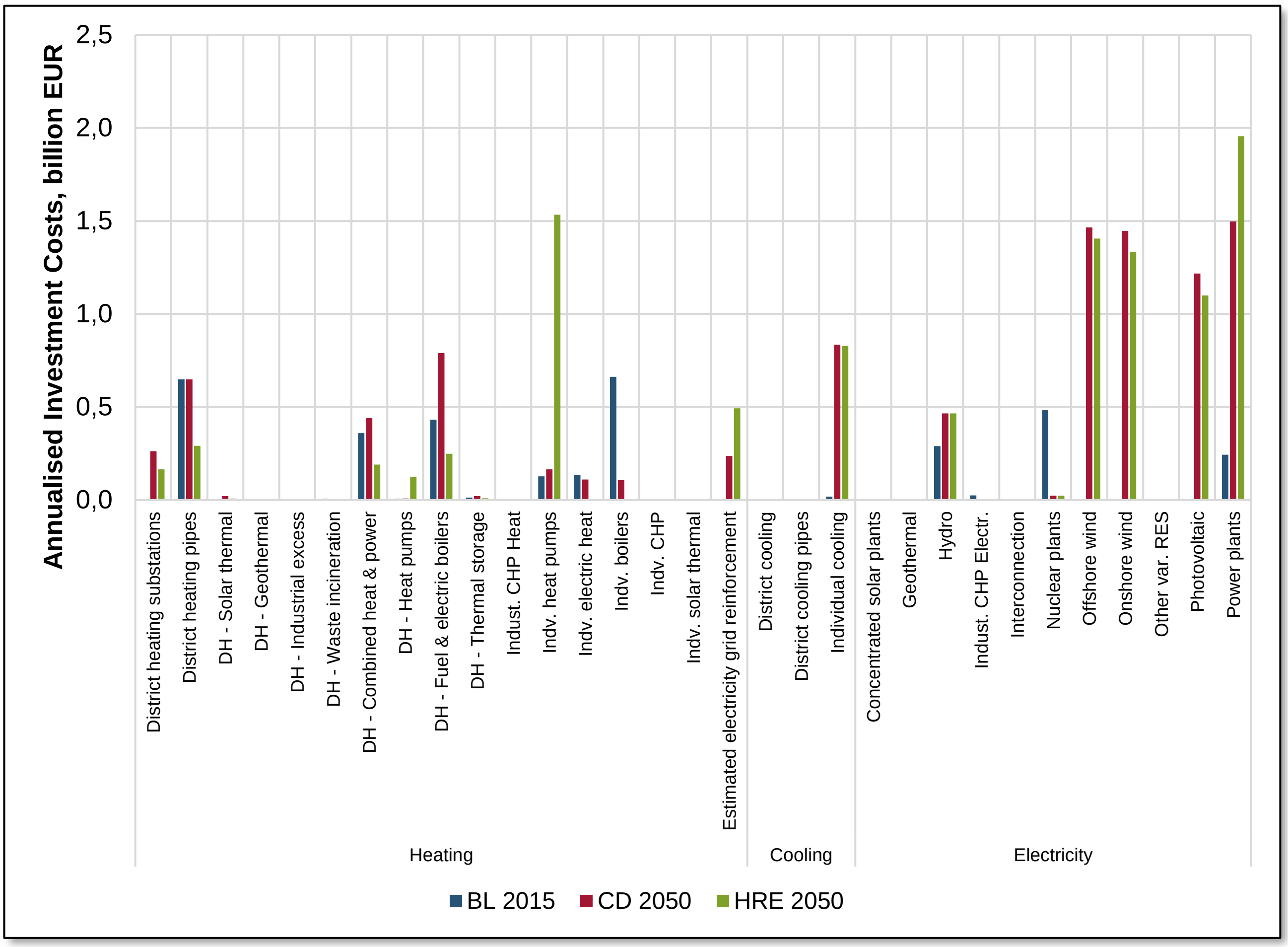


Figure 13. Annualised socio-economic investment costs and categories in Finland, excluding the investment costs necessary for energy savings.

After the heat savings measures, the most relevant new and growing investments for Finland are individual heat pumps, and investments in district heating infrastructure. Of these, the investment in individual heat pumps is most significant, representing about 18% of the investments necessary in the heating sector. This directly mirrors the declining investment in individual boilers. As for savings, these investments often need to be made at the household or business level, so require a different approach and policies that focus on achieving explicit changes in peoples' investment choices.

The redesign of the district energy systems requires investments, but overall the investments in the distribution and transmission infrastructure only represent 3,5% of the investments necessary in the heating sector. In total (including supply technologies, substations, transmission and distribution) the district heating system only comprises 12% of the investments that are necessary. These investments are collective infrastructures, which have high up-front costs and require a policy support in order to ensure collaborative business and procurement models, but finally only represent a small fraction of the annualised investments needed in the heating and cooling sector.

In terms of economy, the energy system in Heat Roadmap Finland reduces the costs of the overall energy system while decarbonising it to a much higher degree. This is primarily achieved by reducing the fuel costs of the energy system, and increasing the levels of investment for energy efficiency measures and technologies in the heating and cooling sector. Given the higher proportion of investments in Heat Roadmap Finland – especially in the built environment – it seems likely that this would both be a driver for local employment, and for an improved balance of payments. While this has not been analysed in detail, it is clear that the scenario presented in Heat Roadmap Finland has the potential to reduce the cost of energy for consumers, assuming that gains are redistributed.

Biomass

No explicit efforts are made to reduce biomass in the Heat Roadmap Finland scenario; the levels used are equal to those developed in a constrained optimisation model development of a conventionally decarbonised energy system [10]. Within a deeply decarbonised energy system, bioenergy is mostly used in condensing power plants in a proportion of 70%, with smaller shares in cogeneration (22%), biofuel production (5%), industrial activities (3%) and the rest in district heating boilers.

However, the final usage is likely to be higher than what could be considered precautionary [3,11,12]. Further research should focus on how the redesign of other sectors can contribute to both the deep decarbonisation and the sustainable use of biomass. In addition, further analysis on how the heating and cooling sector could reduce the use of bioenergy in a nearly zero carbon emissions energy system could contribute to preventing an over-use or overreliance on scarce and potentially unsustainable bioenergy.

Key findings in Heat Roadmap Europe

1	**The heating and cooling sector can be fully decarbonised based on technologies and approaches which already exist, are market-ready and have successfully been implemented in Europe.**

- The HRE 2050 scenarios show that a redesigned and sector-integrated heating and cooling solution can improve the European Union's energy efficiency, economy, and environmental impacts while successfully enabling the transition away from fossil fuels.
- The redesign contributes to keeping global temperature rise under 1,5-2°C as agreed in the Paris Agreement by decarbonising by about 4.300 Mtonnes per year or 86% compared to 1990 levels counting in also non-energy and other sectors such as agriculture. The energy sector emissions are reduced by about 2.700 Mtonnes of CO_2, or by 89% percent compared the 2015 reference. The redesigned energy system does not hinder but enables further implementation of renewable energy. (Figure 14)

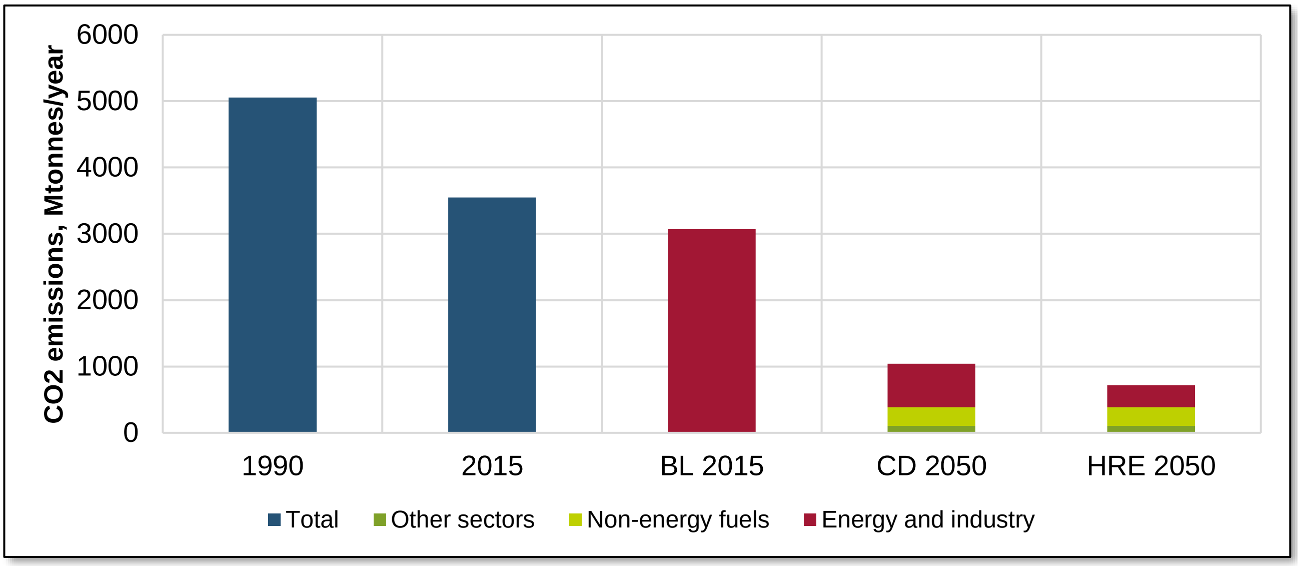


Figure 14. Historical, current and future CO_2 emissions for the 14 HRE4 countries; including the years 1990 [8] (the base year for the Paris Agreement), 2015 and the three 2050 scenarios; i.e. the Baseline (BL) 2050, which represents the development of the energy system under currently agreed policies; the Conventionally Decarbonized (CD) 2050, which represents the development of the energy system under a framework that encourages renewables, but does not radically change the heating and cooling sector; and the HRE 2050, which represents a redesigned heating and cooling system, considering different types of energy efficiency and better integration with the other energy sectors.

- Energy efficiency and decarbonisation in the heating and cooling sector is achieved with the use of already existing technologies, i.e. ambitious renovations of the existing building stock; 3rd generation district heating and cooling grids; efficient heat pumps; and better utilisation of the potential synergies between the energy sectors.

- HRE presents a robust no-regrets pathway: the technologies used are all mature, market-ready and have been implemented in parts of Europe. The challenge is to create integrated knowledge, planning tools, business tools, innovative collaborations and incentives to realise their potential. In most cases it is political and regulatory barriers rather than technical barriers.

2	**Energy efficiency on both the demand and the supply side are necessary to cost-effectively reach the decarbonisation goals.**

- End-user savings alone are not sufficient to decarbonise the heating and cooling system and will increase significantly due to higher investments. Supply side solutions alone require much higher investments in renewable energy and may not be sustainable. Energy efficiency on both the demand and supply side is necessary for a deeper decarbonisation. End-user savings reduce the energy systems' primary energy demand by around 4% (613 TWh) in HRE in 2050 and represent around 30% of total potential savings, with more efficient supply options reducing primary energy a further 8% (1.405 TWh) – which makes up the remaining 70% of total savings.
- An integrated approach to the heating and cooling sector requires more investments to establish energy efficient technologies and infrastructure compared to a focus only on achieving energy efficiency on the demand side. However, overall this reduces energy system costs by approximately 6% (67,4 billion €) annually overall. (Figure 15)
- The reduced consumption of fossil fuels in the heating and cooling strategies in the HRE 2050 scenario almost completely eliminates the dependence on imported natural gas for heating purposes in Europe. The strategies also heavily reduces the vulnerability of citizens to very high heat prices and the risks of energy poverty. Fossil fuels can be reduced by almost 10.400 TWh in 2050 compared to today. The amount of natural gas decreases in 2050 by about 87% compared to today. As comparison 54% of the energy consumption was met by imports, 88% of oil and 70% of natural gas was imported in 2016 [2]. The imported natural gas had a value of 50-65 billion €.
- The reduced expenditure on fuels and higher spending on the suggested investments in local energy efficiency and local resources has the potential to improve local employment and the European balance of payments and reduce expenditures on imported fuels.
- Achieving energy efficiency requires both goals and active policies to support the implementation of infrastructures for heating and cooling within the individual member states' own contexts on the EU level as well as the local level. The existing policies used should be monitored periodically for compliance and changed or expanded if they do not have the desired level of energy savings. A framework for

expanding and establishing thermal infrastructure should be initiated and in line with policies for gas and electricity grids, it should have an EU level and a national level.

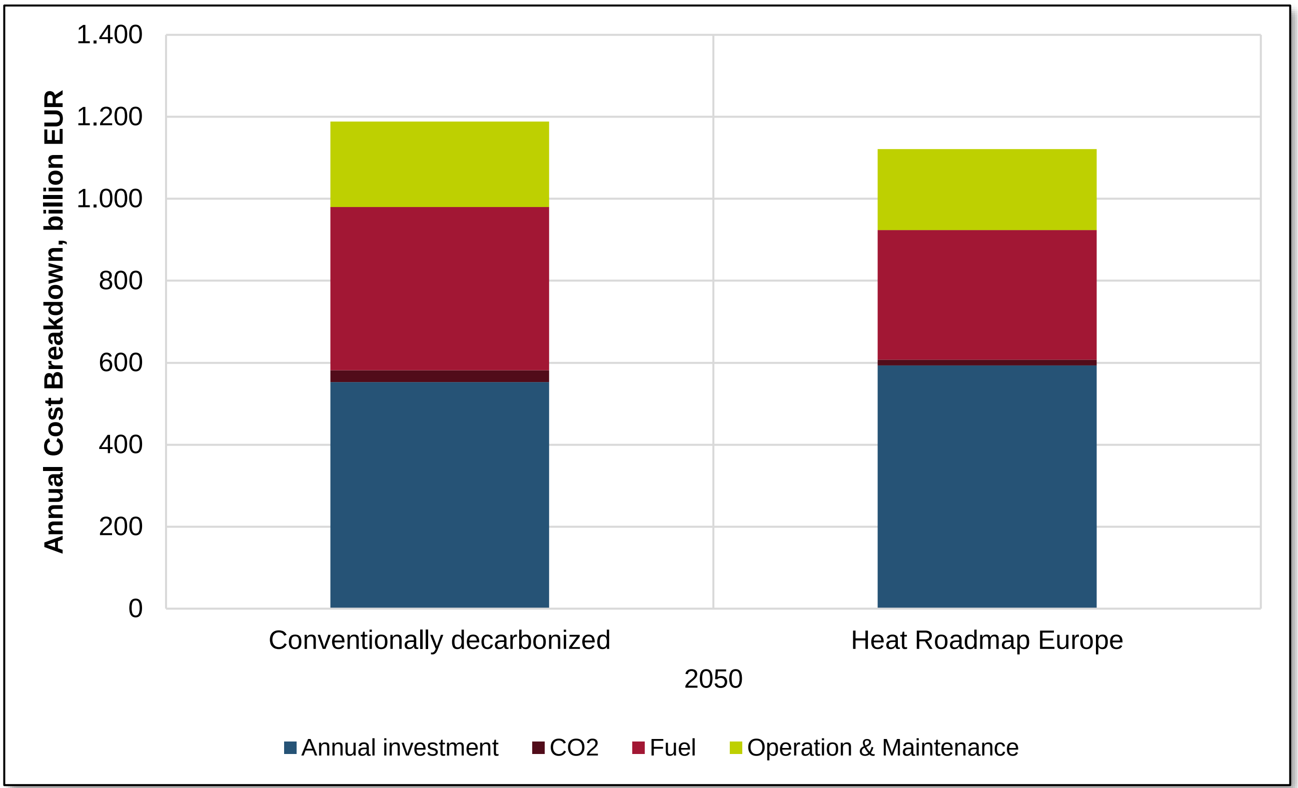


Figure 15. Annual total energy systems costs for the decarbonized 2050 scenarios. The Conventionally decarbonized energy system focusing on increasing the renewable energy penetration and some degree of energy savings reaches an 80% reduction in CO_2-emissions while the HRE 2050 scenarios reaches 86% at a lower cost using deeper renovations and an integrated new energy system design.

3	**More support is needed for implementation and higher energy saving targets for deeper renovation of the existing building stock and investments in industry.**

- **End use savings** are vital to efficiency, decarbonisation and affordability. In existing buildings higher renovation rates and depths are needed. With the current policies and targets, a 25% reduction in total delivered energy for space heating can be reached in 2050, also considering also an increased amount of buildings. This represents an annual refurbishment rate between 0,7% and 1,0% towards 2050, and requires that all policies are fully implemented [4]. In HRE it is recommended to increase the target to at least 30% savings for space heating in buildings. This requires a higher refurbishment rate of 1,5% to 2%, and deeper renovations when they occur [4].

- Both the current and the higher target suggested here require a shift to a much stronger focus and enhanced approach towards **policy implementation** and realisation on a country level, with regular re-evaluations of progress and impact. A higher ambition than 30% for Europe would be precautionary as experience shows that implementation may fail to succeed [9,10] and the results in HRE for most countries show that the socio-economic costs for going higher are very low and within the uncertainties of the analyses.
- HRE finds that all countries should have a higher ambition level that the current EU level target would lead to. Especially Belgium, the Czech Republic, Hungary, the Netherlands, Poland, and Romania should have a higher energy savings target. No savings are implemented in the hot water demands.

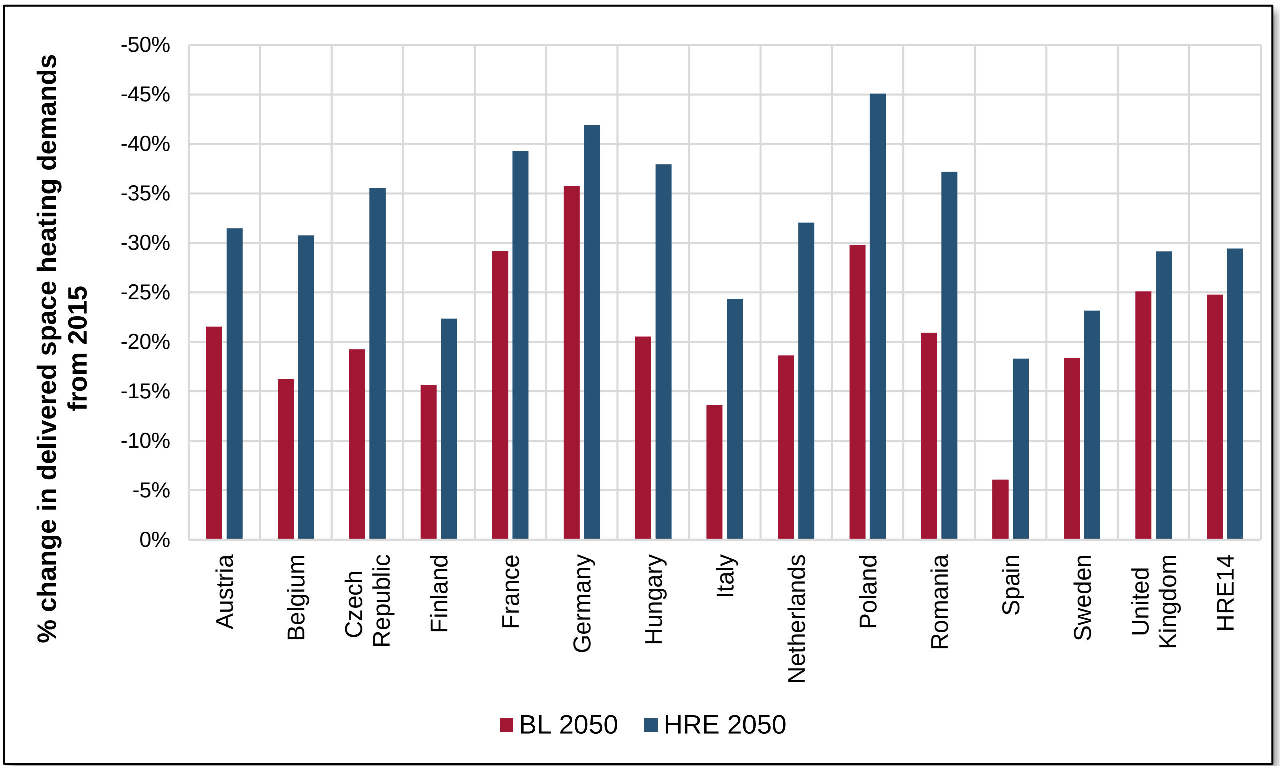


Figure 16. Heat Roadmap Europe and Baseline 2050 (current policies) changes in the delivered space heating in 2050 if fully implemented.

- The HRE4 results show that energy savings in industry and the service sector are highly cost-effective from a socio-economic and energy perspective, meaning that efficiency standards and financial incentives for process heat savings should also be ensured in member states. The savings recommended in Heat Roadmap Europe are 8% for process heating, which is the highest considered technically feasible within the proven-technology approach in HRE. Like for space heat savings, a strong focus on implementation can be recommended. (Figure 17)

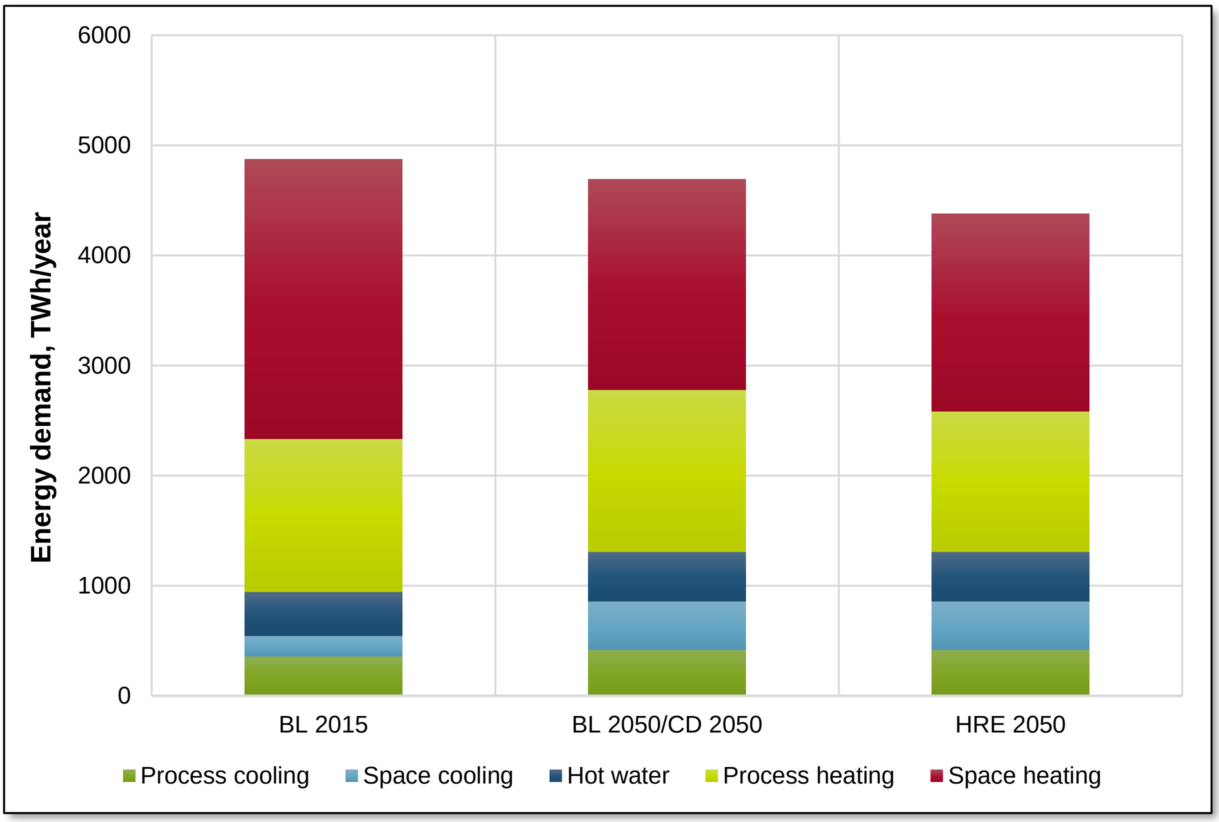


Figure 17. Heating and cooling demands reductions in the baseline (BL) and decarbonized (CD) scenarios and in Heat Roadmap Europe 2050.

4	**In the vast majority of urban areas, district energy is technically and economically more viable than other network and individual based solutions, and can be 100% decarbonised through the use of renewables, large heat pumps, excess heat, and cogeneration.**

- The analyses show that district heating cost-effectively can provide at least half of the heating demand in the HRE4 countries while reducing the primary energy demand and CO2-emissions. For the 14 HRE countries combined, a 0,5% total cost change interval gives a market share of district heating in a 32-68% range in combination with the 30% end demand energy savings. The scenario level (45%) where about half of the heat market is covered with district heating is based on economic metrics and effects on the energy system only.
- Due to a number of additional strategic benefits, such as security of supply as well as jobs and industrial development it can be recommended to go beyond the modelled or current district heating share towards 70%. While there are

differences from country to country, going beyond the modelled level towards the maximum feasible level can further lower the price fluctuations citizens will experience, lower geopolitical tensions connected to energy supply and create an even more fuel-efficient system. (Figure 18)

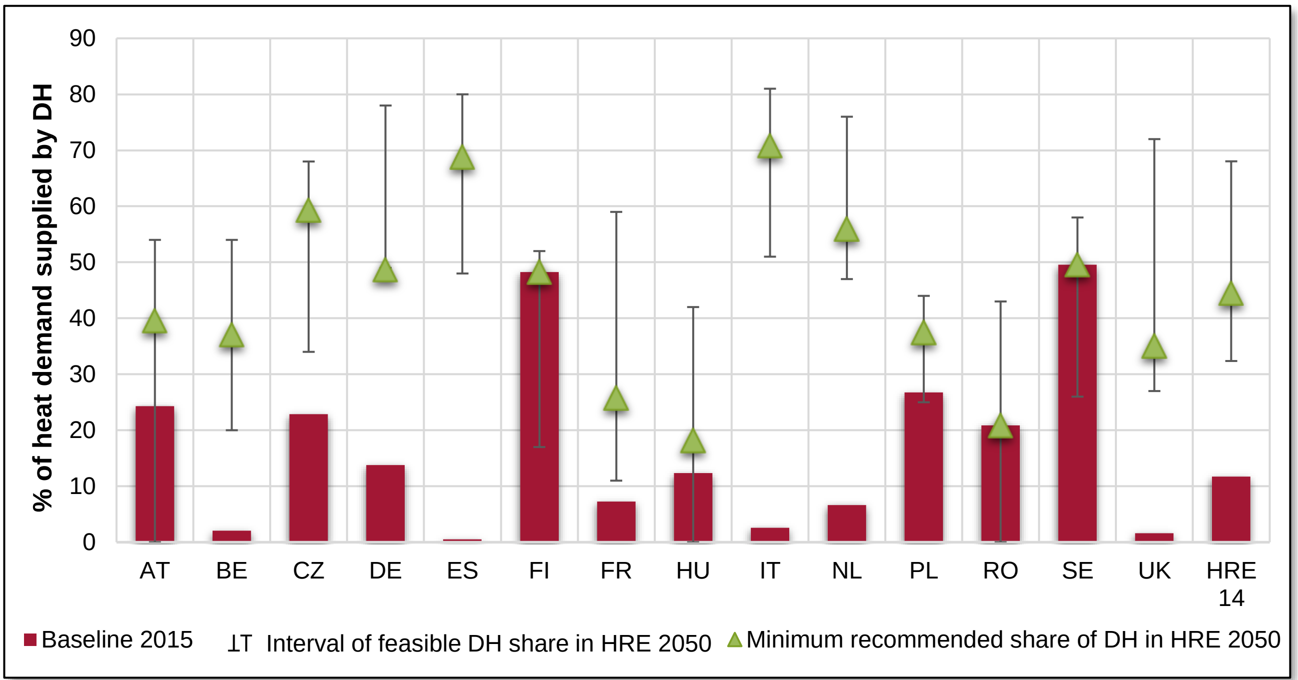


Figure 18. Baseline share of district heating in 2015 and the minimum recommended level of district heating share in HRE4. The range bars represent the amount of district heating that is economically feasible within a 0,5% total annual energy system cost change sensitivity. The recommended minimum levels take into account cost efficient levels and current level of district heating. Going beyond this level can generally increase energy efficiency.

- The level of district heating recommended is robust against a situation where the implementation of energy savings and refurbishments fails.
- Future production and storage units for district heating must be more varied and versatile to integrate low-carbon sources and enable flexibility. Excess heat from electricity production (CHP) covers 25-35% of the heat generation, large heat pumps covers 20-30% using mainly renewable energy. The remaining heat supply is from industrial excess heat (25%) and other renewable sources such as geothermal and solar thermal heating (5%). Renewable sources such as deep geothermal energy and solar thermal heating are geographically and temporally constrained, and can only be exploited to their full potential in the energy system if district heating is present. The capacity of boilers can cover the peak demands over the year. Heat only boilers play a marginal role in the heat supply mix (less than 6%).
- The most important thermal energy storage to consider is in local feasibility studies can cover on average 2-8 hours in larger cities and 6-48 hours in smaller cities. These types of short-term storages are crucial to balance the electricity grid as well as to handle fluctuating local low value heat sources. Seasonal storages may

be relevant to locally increase the coverage of excess heat otherwise it is wasted in the summer period from e.g. industry, waste incineration or solar thermal.

- Full electrification of the heating supply is more costly and neglects the potential to recover energy from industry and power generation, limiting the overall efficiency of the system and possibility for coupling electricity, heating and using heat storage. With 50% district heating or more in combination with electrification overall the grid costs are spread between thermal and electricity grids. Lower shares of district heating will increase the cost for electricity grids in decarbonised energy systems. A further benefit of higher district heating shares are potential higher usages of domestic fuel or EU fuels creating a better balance of payment and potential increase in jobs.

5	**In areas with limited district heating and cooling feasibility, individual supplies should be from heat pumps that can contribute to the integration of variable renewables.**

- In rural areas, heat pumps should become the preferable individual solution based on their high efficiency, providing about half of the heat demand or lower. The level depends on the local conditions for the built environment. High standards of energy performance and deep renovations are necessary in order to implement heat pumps effectively and ensure high coefficients of performance (COPs) along with a high level of comfort.
- Heat pumps reduces the dependency on fuel boilers in a bioenergy-scarce decarbonised future and increases the use of fluctuating renewable electricity sources. It can also to some extent contribute to the energy system flexibility [11]. While these heat pumps can in reality be combined with solar thermal and biomass boilers as part of the supply in some areas in Europe, in this study all individual heating is supplied by heat pumps as a modelling method due to the purpose of the analysis and their distinct advantage of efficiency and integration with the electricity sector.
- Thermal storage in combination with these are important, but the flexibility in these storage is limited compared to the district heating system with larger thermal storage that have much lower costs, larger heat pumps, combined heat and power, etc. [12,13].
- Operational incentives for building residents should first and foremost promote energy savings and then flexible interaction for consumers to help balance the electricity grid and not maximise self-consumption since optimising in the building level will most likely result in higher costs for the overall energy system [14].

6 **Cooling demands are less significant compared to the heating demands, but are expected to increase in the future. The knowledge about solution designs is expected to improve in the future.**

- Cooling demands are expected to increase in all countries according to the saturation levels, which could more than double. However, even in the most southern HRE4 countries, heat demands dominate the sector, as in 2050 cooling represents 20% of the thermal energy demand in the modelled scenarios.
- In HRE4, a full overview is presented for the first time of the potential cooling technologies looking towards 2050 [15]. These solutions contribute to the efficient use of energy through high seasonal efficiency, absorption of different types of excess energy, and the recovery of energy from seawater and lakes.
- The cooling demands differ from heating in that they are more balanced between space cooling and process cooling, and dominated by the service and industries rather than the residential sector. This requires a broader understanding of how district cooling could be modelled and replicated on a spatial level.

7 **The heating and cooling sector can play an important role by integrating the increasing shares of variable renewable energy and enhance the grid flexibility.**

- HRE has an integrated approach, which aims utilise the synergies between the energy sectors through the use of heat pumps, thermal storage, combined heat and power, and industrial heat recovery.
- The use of renewable electricity and thermal storage in the heating and cooling sector can help balance the electricity grid when high levels of variable renewable energy are introduced.
- The modelling shows that an energy system with a strategically decarbonised heating and cooling sector can support a similar amount of wind capacity as a conventionally decarbonised energy system. At the same time up to 30% more of the electricity produced by the installed variable renewable energy capacity can be functionally absorbed and used in the energy system due to the enhanced flexibility in the heating and cooling sector.
- The redesign of the suggested European energy system represents a step that can enable a deeply decarbonised energy system. Extending the HRE designs to use a Smart Energy Systems approach to include transport and electrofuels could provide a pathways towards 100% renewable energy to fully decarbonise the Energy Union [16–18].

8	**Tools and methodologies that are specific to the sector are necessary in order to coherently model, analyse, and design the heating and cooling system within the energy system. This is an important part of developing pathways and strategic plans that contribute to a decarbonised energy system for the future**

- Heating and cooling is the largest sector in the European energy system, and without a decarbonisation of this sector it will not be possible to achieve the reductions in CO_2 emissions needed to prevent global temperature rises.
- This includes detailed spatial analysis in order to be able to understand the local nature of heating and cooling, which is necessary since infrastructure costs for thermal energy are higher and thermal energy sources cannot travel well without increased losses.
- An in-depth and bottom-up understanding of the built environment and industries is necessary to understand and analyse the thermal sector and thermal energy demands. This forms the base of any strategic heating and cooling development and creates an understanding of possible energy savings.
- An energy system analysis approach is necessary to ensure that a decarbonised energy system does not exist in isolation. A combination of a tool that can model energy systems as they evolve through time, and a simulation tool that can analyse the hourly variations of demands and resources (and necessary capacities) has allowed for a coherent analysis of the design and development of a heating and cooling sector that can be integrated into a wider decarbonised energy system.

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